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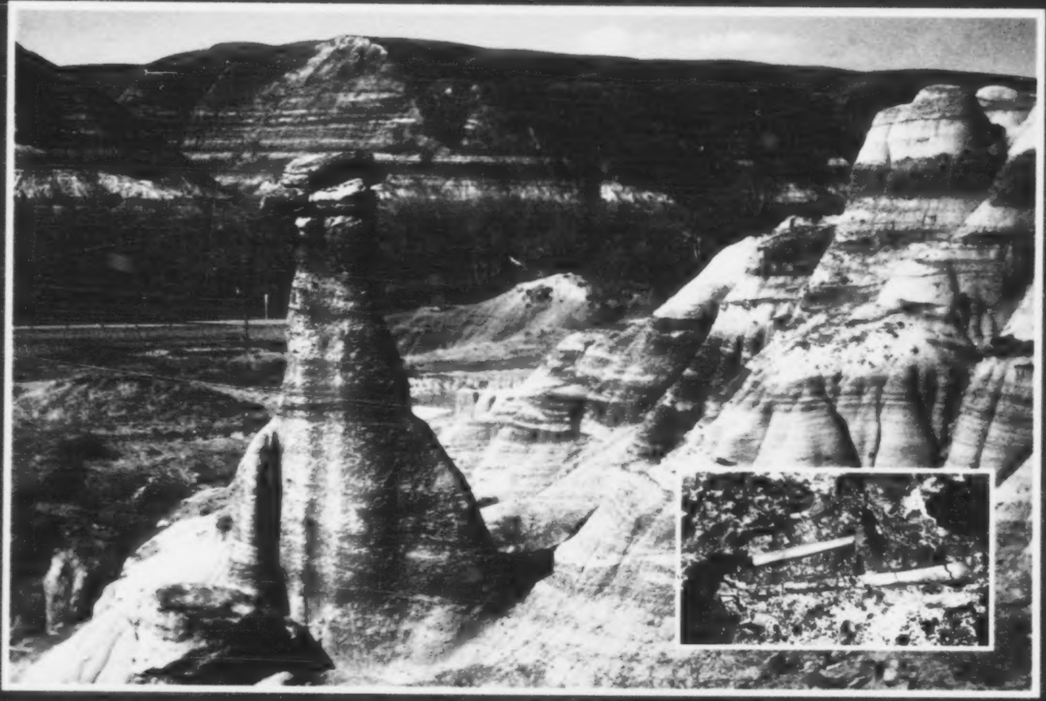
THE HORSESHOE CANYON FORMATION IN SOUTHERN ALBERTA: SURFACE AND SUBSURFACE STRATIGRAPHIC ARCHITECTURE, SEDIMENTOLOGY, AND RESOURCE POTENTIAL

A.P. Hamblin



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Cover Illustration
Hoodoos are picturesque pillars of rock formed by the differential erosion of horizontal strata with layers of varying hardness. In this case, the more resistant caprock protecting the softer pedestal beneath is a sandy sideritic concretion. The pale grey sandstone comprising the pillar, and characterized by well-developed inclined heterolithic stratification, represents a multistoried estuarine incised valley deposit at the base of the Hoodoo tongue of the Horseshoe Canyon Formation. The background cliffs display the thinly interbedded sandstone, siltstone and coal seams typical of the formation (GSC photo 4762-1).
Inset: Dinosaur remains are common in strata of the Horseshoe Canyon Formation in the Red Deer River valley. This hadrosaur limb bone was found at the base of a thin fluvial channel sandstone in the Tolman tongue (GSC photo 4762.3).

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CONTENTS

1 Abstract
2 Résumé
3 Summary
4 Sommaire
7 Introduction
7 Rationale and objectives
7 Study area, measured sections, and subsurface database
11 New informal stratigraphic nomenclature and minor revision
12 Tectono-sedimentary analysis of basin-fill successions
13 Acknowledgments
13 General tectonic and depositional setting
13 Regional foreland basin setting
13 Laramide Orogeny and basin infill
14 Regional Upper Cretaceous–Tertiary internal stratigraphy
14 The upper Campanian/Maastrichtian sequence in the WCSB context
17 Horseshoe Canyon Formation: stratigraphic setting and revision
17 Previous work
20 Present work (minor revision)
20 Horseshoe Canyon Formation (formal revision of upper boundary)
23 Coal zones
25 Paleoclimate
25 Paleontology
26 Relation to other units
28 Informal lithostratigraphic subdivision
28 Introduction
29 Strathmore tongue (new informal unit)
30 Hoodoo tongue (new informal unit)
31 Midland tongue (new informal unit)
33 Tolman tongue (new informal unit similar to a unit informally defined by Srivastava, 1968)
34 Carbon tongue (new informal unit)
35 Three-dimensional geometry and distribution
35 Surface and subsurface correlation
37 7-12-25-25W4
37 Regional cross-sectional geometry and correlation
39 Distribution and plan-view geometry
40 Isopach maps
51 Sedimentological background
51 Summary of previous interpretations
55 Petrography
55 Paleopedogenetic deposits
59 Descriptions and interpretations of Horseshoe Canyon facies
59 Middle–upper Bearpaw facies
60 Strathmore tongue facies
60 Hoodoo tongue facies
63 Midland tongue facies
67 Tolman tongue facies
70 Carbon tongue facies
72 Previously recorded paleocurrent data
74 New paleocurrent data
77 Stratigraphic architecture: Bearpaw-Horseshoe Canyon cycles
77 3-D geometrical framework
79 Cycle A (lower Bearpaw-Strathmore: maximum transgression)
79 Cycle B (middle Bearpaw-Hoodoo)
79 Cycle C (upper Bearpaw-Midland)

- 80 Cycle D (DMT-Tolman)
- 80 Cycle E (Carbon: maximum regression)
- 81 Correlation with distal marine sequences
- 82 Regional framework and tectonic factors
  - 82 Tectonic controls
  - 83 Regional framework
  - 84 Coals and regional transgressions
  - 85 Paleosols and regional regressions
  - 85 Summary
- 86 Shallow gas potential
  - 86 General
  - 86 Lower Horseshoe Canyon shoreline play family
  - 86 Middle–Upper Horseshoe Canyon nonmarine fluvial play family
- 90 Coalbed methane potential
  - 90 General
  - 90 Horseshoe Canyon Formation
- 93 Water resource potential
  - 93 General
  - 93 Bearpaw Formation
  - 93 Horseshoe Canyon Formation
- 94 Conclusions
- 96 References

Appendix

- 103 A Measured sections, locations and raw paleocurrent data
- 175 B Horseshoe Canyon Formation subsurface tops
- 180 C Horseshoe Canyon Formation gas pools, Alberta

Figures

- 8 1. Study area, outcrop area, subsurface cross-sections, and core utilized in this study
- 9 2. a) Outcrop and core measured-section locations, b) transect along Red Deer River, c) transect along Rosebud River, and d) transect along Kneehills Creek
- 15 3. Nonmarine clastic wedges and marine shale units of post-Colorado Sequence, with Bearpaw-Horseshoe Canyon formations highlighted
- 16 4. Simplified correlation chart for post-Colorado strata in WCSB
- 17 5. Isopach of the Bearpaw Formation, southern Alberta and Saskatchewan
- 18 6. Isopach of the Horseshoe Canyon Formation, southern Alberta
- 19 7. Historical attempts at internal subdivision of the Horseshoe Canyon Formation
- 20 8. Horseshoe Canyon composite type section
- 27 9. Generalized stratigraphic correlation chart for upper Campanian–Maastrichtian strata in the WCSB
- 29 10. Comparison of nomenclature of Irish (1970) vs. the framework established in this study
- 36 11. Subsurface gamma-ray-neutron log and core description for C.P.O.G. Strathmore EV 7-12-25-25W4 core
- 37 12. Location of C.P.O.G. Strathmore EV 7-12-25-25W4 core
- 38 13. Comparison of core section from C.P.O.G. Strathmore EV 7-12-25-25W4 well with outcrop sections from the Red Deer and Rosebud rivers
- CD-ROM 14. West-east stratigraphic cross-section of Bearpaw-Horseshoe Canyon strata in Township 20
- CD-ROM 15. West-east stratigraphic cross-section of Bearpaw-Horseshoe Canyon strata in Township 30
- CD-ROM 16. West-east stratigraphic cross-section of Bearpaw-Horseshoe Canyon strata in Township 40
- 41 17. Isopach of Lower Bearpaw tongue
- 42 18. Isopach of Strathmore tongue
- 43 19. Isopach of Middle Bearpaw tongue
- 44 20. Isopach of Hoodoo tongue
- 45 21. Isopach of Upper Bearpaw tongue
- 47 22. Isopach of Midland tongue
- 48 23. Isopach of Drumheller marine tongue
- 49 24. Isopach of Tolman tongue

50 25. Isopach of Carbon tongue
56 26. Diagnostic paleosol features
57 27. Flow chart for classifying paleosol orders
59 28. Marine mudstone of the Bearpaw Formation middle tongue, overlain by interbedded sandstone, mudstone, and coal of the Hoodoo tongue
59 29. Bioturbated claystone with *Ophiomorpha* burrows and thin siltstone beds, Bearpaw Formation middle tongue
60 30. Very fine-grained sandstone beds interbedded with bioturbated mudstone, Bearpaw Formation middle tongue
60 31. Thickening- and coarsening-upward sequence at the top of the Bearpaw Formation middle tongue, overlain by the Hoodoo tongue
61 32. Interbedded lithologies typical of the Hoodoo tongue
61 33. Fine-grained sandstone in multistoried channel body, Hoodoo tongue
61 34. Fining-upward sandstone erosively overlying thick coal, Hoodoo tongue
61 35. Scoured base and flat top of sandstone channel, upper Hoodoo tongue
62 36. Sandstone channel, with abundant trough-crossbedding and IHS bedding, fining upward to coal, Hoodoo tongue
62 37. Interbedded sandstone and siltstone IHS-dominated unit, overlain by thick coal, Hoodoo tongue
62 38. Bioturbated marine mudstone, Bearpaw Formation middle tongue, overlain by the Hoodoo tongue
62 39. IHS sets in meandering incised valley, Hoodoo tongue
63 40. Sideritic calcisol with roots and wood fragments, Hoodoo tongue
63 41. Laterally continuous histosol, top of Hoodoo tongue, overlain by the Midland tongue
63 42. *Ophiomorpha* and *Planolites* burrows, in tidally influenced channel sandstone, Hoodoo tongue
63 43. Interbedded sandstone, siltstone and minor coal of the Midland tongue
64 44. Interbedded sandstone, siltstone, and minor coal of the Midland tongue, overlain by pedogenic siltstone of the Tolman Member
64 45. Multistoried sandstone channel, with stories separated by interbedded sandstone and siltstone, Midland tongue
65 46. Lag of small caliche nodules in trough-crossbedded sandstone, Midland tongue
65 47. Trough-crossbed set in sandstone channel unit, Midland tongue
65 48. Broad, shallow channel-fill lens of sandstone, Midland tongue
65 49. Pedogenic siltstone with calcisol horizons filling scour in sandstone, Midland tongue
66 50. Laterally extensive sandstone splay lens, encased in overbank pedogenic siltstone with calcisol horizons, Midland tongue
66 51. Massive, blocky, pedogenic siltstone vertisol, underlain and overlain by coal seams, Midland tongue
66 52. Hummocky cross-stratification in sandstone bed, at Hoodoo-Midland contact
66 53. Vertical *Skolithos* burrows in coarsening-upward sandstone, at Hoodoo-Midland contact
67 54. Tolman tongue pedogenic siltstone, overlying coaly mudstone of the Midland tongue
67 55. Tolman tongue pedogenic siltstone, overlain by dark mudstone and coal of the Carbon tongue
68 56. Massive, blocky, rubbly, pedogenic siltstone vertisol, Tolman tongue
68 57. Massive, blocky, rubbly, pedogenic siltstone vertisol, with ped structures, Tolman tongue
68 58. Laterally continuous sideritic calcisol horizon with sharp top, encased in pedogenic siltstone, Tolman tongue
68 59. Laterally continuous sideritic calcisol with sharp top, gradational base, vertical fractures and roots, Tolman tongue
69 60. Lenticular splay sandstone with scoured base and flat top, encased in pedogenic siltstone, Tolman tongue
69 61. Laminated mudstone with oyster shells, capped by sideritic concretion bed and pedogenic siltstone, Drumheller marine tongue
69 62. Calcareous sandstone overlain by limestone with oyster shells, Drumheller marine tongue
70 63. In situ bivalve shells in calcareous, burrowed sandstone, Drumheller marine tongue
70 64. Abundant *Skolithos* and *Planolites* burrows in calcareous sandstone with oyster shell fragments, Drumheller marine tongue
70 65. Interbedded sandstone, siltstone, and coal, Carbon tongue
71 66. Interbedded sandstone, siltstone, and coal, with distinctive white sandstone of Carbon tongue overlain by black mudstone of the Battle Formation
71 67. Thick, coarse-grained sandstone of basal Scollard Formation, sharply overlying dark grey mudstone of the Battle Formation

71 68. Multistoried, fining-upward sandstone channel, overlain by carbonaceous mudstone, Carbon tongue
71 69. Trough-crossbed sets in sandstone channel, Carbon tongue.
72 70. White quartz-kaolin spodosol sandstone of Whitemud sandstone of the Carbon tongue, overlain by black, bentonitic mudstone of the Battle Formation
72 71. Giant sideritic concretion with septarian crack network, part of a laterally extensive calcisol horizon, Carbon tongue
72 72. Laterally continuous coal histosol, overlain by sandstone, Carbon tongue
73 73. Black bentonitic mudstone of the Battle Formation, with thin Kneehills Tuff, overlying the Carbon tongue
73 74. Vesicular Kneehills Tuff claystone, Battle Formation, overlain by pedogenic siltstone and Scollard Formation sandstone
74 75. Horseshoe Canyon Formation paleoflow indicators
75 76. Hoodoo tongue paleoflow indicators
75 77. Midland tongue paleoflow indicators
76 78. Tolman tongue paleoflow indicators
76 79. Carbon tongue paleoflow indicators
77 80. Schematic conceptual northwest-southeast cross-section of Bearpaw Formation-Horseshoe Canyon Formation depositional system in south-central Alberta
81 81. Paleogeography during the time of Bearpaw-Horseshoe Canyon Formation deposition
87 82. Play area and discovered gas pools, lower Horseshoe Canyon Formation, Marine Shoreline Play Family
88 83. Pool-size-by-rank plot, lower Horseshoe Canyon Formation, Marine Shoreline Play Family
89 84. Play area and discovered gas pools, middle–upper Horseshoe Canyon Formation, Nonmarine Fluvial Play Family
91 85. Pool-size-by-rank plot, middle–upper Horseshoe Canyon Formation, Nonmarine Fluvial Play Family

THE HORSESHOE CANYON FORMATION IN SOUTHERN ALBERTA: SURFACE AND SUBSURFACE STRATIGRAPHIC ARCHITECTURE, SEDIMENTOLOGY, AND RESOURCE POTENTIAL

ABSTRACT

Upper Campanian–Maastrichtian strata of the Horseshoe Canyon Formation have received little modern stratigraphic analysis on a regional scale, even though they are well exposed in the famous "Drumheller Badlands" along the Red Deer River, are present in thousands of drillholes in southern Alberta, and are endowed with significant coal and gas resources. Hence there is no regionally applicable subdivision, subsurface mapping, or appreciation of reservoir geometries and exploration strategies.

Regional stratigraphic analysis of integrated surface and subsurface data from the Horseshoe Canyon Formation of south-central Alberta indicates the unit represents a third-order, southeastward-thinning, progradational system that advanced hundreds of kilometres into the Bearpaw marine basin over about 6 to 7 million years of Late Cretaceous time. The upper boundary of the Horseshoe Canyon Formation is herein formally revised to coincide with the regional unconformity present between strata of the Whitemud sandstone and the dark shale of the Battle Formation. The former "Whitemud Formation" is therefore downgraded to an informal pedogenic unit beneath this surface. In addition, the unit is clearly subdivisible into five previously unrecognized, regionally mappable informal lithostratigraphic tongues. In this study area, these comprise stacked composite, primarily regressive units that extend toward the southeast and are separated by tongues of marine shale extending toward the northwest from the main body of coeval Bearpaw Formation shale. In ascending order, these new informal tongues are here referred to as Strathmore, Hoodoo, Midland, Tolman, and Carbon, and are characterized by thinly interbedded sandstone, siltstone, coal, and various types of paleosol horizons. The tongues identified here may eventually warrant formal member status but at present, the definitions of their boundaries are inadequate for formalization. Paleoflow indicators suggest the direction of general sediment dispersal was toward the east-southeast, but that over time, dispersal tended more toward the east. Differences in paleosol type and abundance, and in coal thickness and abundance, suggest a climatic trend of most humid in the Strathmore to most arid in the Tolman, then back to humid again in the Carbon.

The five Horseshoe Canyon nonmarine tongues, and the Bearpaw marine tongues that separate them, form a stacked set of asymmetrical, shallowing-upward, fourth-order regressive cycles with regional extents. In ascending order, these cycles are A) lower Bearpaw-Strathmore tongues, B) middle Bearpaw-Hoodoo tongues, C) upper Bearpaw-Midland tongues, D) Drumheller marine-Tolman tongues, and E) Carbon tongue. The locus of shoreline-related sandy deposition and the penetration of marine influence shifted southeastward (basinward) through time, denoting an overall regressive trend. The lowest Bearpaw marine tongue includes the maximum transgression phase immediately overlying the Belly River Group, whereas the subaerial unconformity at the top of the Carbon tongue represents the maximum regression surface. This unconformable top of the Horseshoe Canyon Formation is marked by the distinctive Whitemud sandstone, here interpreted as an intensely altered spodosol horizon, and is overlain by the black mudstone of the Battle Formation. Both the third-order transgressive-regressive sequence of the Dinosaur Park-Bearpaw-Horseshoe Canyon formations, and the contained fourth-order regressive cycles, are the result of fundamental regional tectonic controls on subsidence and sediment supply. In addition, nested within each fourth-order cycle is a series of thinner, asymmetrical, coarsening-upward, fifth-order, regressive subunits that mimic the thinning and fining trends of the larger cycles. These units include separate mappable reservoir or aquifer trends of channel, estuarine and shoreface character, and several of them have been studied in detail by other authors at the famous Hoodoos-Willow Creek location. The Horseshoe Canyon Formation contains potential for significant and under-exploited shallow gas, coalbed methane, and groundwater resources. More focussed exploration efforts resulting from the conclusions of this study may increase the economic benefits derived from these strata.

RÉSUMÉ

Les strates de la Formation de Horseshoe Canyon du Campanien supérieur-Maastrichtien n'ont fait l'objet que d'un petit nombre d'analyses stratigraphiques modernes d'échelle régionale et ce, en dépit du fait qu'elles sont bien exposées dans les «badlands de Drumheller» le long de la rivière Red Deer, qu'elles sont recoupées par des milliers de forages dans le sud de l'Alberta et qu'elles renferment d'importantes ressources en charbon et en gaz naturel. Par conséquent, il n'existe aucune subdivision régionale de ces strates ni aucune cartes de leur subsurface. La géométrie des roches réservoirs et les stratégies visant à les explorer n'ont pas non plus été établies.

L'analyse stratigraphique régionale de données intégrées de surface et de subsurface tirées de la Formation de Horseshoe Canyon, dans le centre sud de l'Alberta, indique que l'unité représente un système de progradation de troisième ordre qui s'amincit vers le sud-est et qui s'est avancé sur des centaines de kilomètres dans le bassin marin de Bearpaw sur une période d'environ 6 à 7 millions d'années, au cours du Crétacé tardif. Dans le présent document, la limite supérieure de cette formation est formellement repositionnée afin qu'elle corresponde à la discordance régionale qui est située entre les strates du grès de Whitemud et le shale foncé de la Formation de Battle. L'ancienne «Formation de Whitemud» a donc été déclassée et est maintenant considérée comme une unité pédogénétique informelle sous cette surface. En outre, l'unité peut manifestement être subdivisée en cinq langues lithostratigraphiques informelles, non reconnues auparavant, qui peuvent être cartographiées à l'échelle régionale. Dans la région à l'étude, ces langues constituent des unités composites empilées principalement régressives, qui s'étendent vers le sud-est et qui sont séparées par des langues de shale marin se prolongeant vers le nord-ouest à partir de la masse principale de shale contemporain de la Formation de Bearpaw. Dans le présent bulletin, ces nouvelles langues informelles sont appelées, en ordre ascendant, Strathmore, Hoodoo, Midland, Tolman et Carbon. Elles se caractérisent par la présence de minces interstratifications de grès, de siltstone, de charbon et de divers types d'horizons de paléosol. Ces langues pourraient éventuellement être considérées comme des membres formels, mais pour l'instant, la définition de leurs limites ne le permet pas. Des indicateurs de paléo-écoulement laissent supposer que les sédiments ont été dispersés en général vers l'est-sud-est, puis davantage vers l'est au fil du temps. On trouve des différences dans les types de paléosols et leur abondance ainsi que dans l'épaisseur et l'abondance du charbon, ce qui porte à croire que les conditions climatiques représentées vont de très humides, dans la langue de Strathmore, à très arides, dans la langue de Tolman, et enfin à humides, dans la langue de Carbon.

Les cinq langues non marines de la Formation de Horseshoe Canyon et les langues marines de la Formation de Bearpaw qui les séparent forment un empilement de cycles régressifs asymétriques de quatrième ordre; ces cycles régressifs ont une étendue régionale et témoignent d'une diminution de la profondeur vers le haut de la séquence. Ces cycles sont les suivants, donnés par ordre ascendant : A) les langues inférieures de Bearpaw-Strathmore; B) les langues intermédiaires de Bearpaw-Hoodoo; C) les langues supérieures de Bearpaw-Midland; D) les langues de Drumheller (marine)-Tolman; et E) la langue de Carbon. Le foyer d'accumulation des dépôts sableux associés au rivage et l'aire d'influence marine se sont déplacés vers le sud-est (vers le bassin) au fil du temps, ce qui témoigne d'une tendance régressive globale. La plus inférieure des langues marines de Bearpaw comprend la phase de transgression maximale sus-jacente au Groupe de Belly River, alors que la discordance subaérienne au sommet de la langue de Carbon représente la surface de régression maximale. Ce sommet discordant de la Formation de Horseshoe Canyon est marqué par la présence du grès distinctif de Whitemud, que nous interprétons ici comme un horizon de podzol fortement altéré et qui est recouvert par le mudstone noir de la Formation de Battle. La séquence trangressive-régressive de troisième ordre des formations de Dinosaur Park, de Bearpaw et de Horseshoe Canyon, ainsi que les cycles régressifs de quatrième ordre qu'elles contiennent, sont les produits de facteurs tectoniques régionaux fondamentaux agissant sur la subsidence et l'apport de sédiments. De plus, chaque cycle de quatrième ordre renferme une série de sous-unités régressives asymétriques plus minces de cinquième ordre, à granoclassement inverse, qui reproduisent les tendances en matière d'amincissement et de granodécroissance des cycles plus gros. Ces unités peuvent renfermer des réservoirs ou des aquifères qu'il est possible de cartographier et qui sont caractéristiques de chenaux, d'estuaires et d'avant-plage. Plusieurs d'entre elles ont été étudiées en détail par d'autres auteurs sur le site renommé de Hoodoos-ruisseau Willow. La Formation de Horseshoe Canyon pourrait contenir d'importantes réserves sous-exploitées de gaz naturel peu profond, de méthane des gisements de charbon et d'eaux souterraines. Des travaux d'exploration plus ciblés basés sur les conclusions de la présente étude pourraient accroître les avantages économiques associés à l'exploitation de ces strates.

SUMMARY

To more fully understand the regional stratigraphy, sedimentology and resource potential of the sandy upper Campanian–Maastrichtian strata of southern Alberta, a series of outcrop measured sections and nearby subsurface well cross-sections were studied. Because these strata have received attention in only one, heavily visited outcrop area, and little subsurface study, part of this report synthesizes the scattered previous literature, providing a solid framework for the following interpretations. This study attempts to a) correlate and integrate data from both surface outcrops and nearby subsurface well-logs to delineate regional depositional trends and a more recognizable subdivision of the strata, b) present the regional stratigraphic architecture, lithofacies and sedimentological interpretations inherent in the late Campanian–Maastrichtian strata, c) delineate a tentative regionally applicable stratigraphic framework, starting from the more distal area of intertonguing with the coeval Bearpaw Formation and projecting to more proximal areas, and d) examine the potential for enclosed hydrocarbon, coal and groundwater resources.

The first-order foreland basin succession of the Western Canada Sedimentary Basin includes a Campanian to Paleocene, second-order, composite coarsening-upward, eastward-thinning wedge, up to 3.5 km thick, which represents the final stage of foreland evolution. The third-order late Campanian–Maastrichtian sequence, part of which is examined in this study, was deposited on the northwest margin of the major north–south Bearpaw inland seaway, synchronous with part of the deformation associated with the collision of Insular Superterrane with Intermontane Superterrane. This third-order Dinosaur Park-Bearpaw-Horseshoe Canyon Sequence is bounded by unconformities: the sub-Dinosaur Park unconformity at the base, and the post-Horseshoe Canyon unconformity at the top. The maximum flooding surface, located just above the top of the Belly River Group, separates the transgressive systems tract (Dinosaur Park) from the regressive systems tract (Bearpaw-Horseshoe Canyon). The progradational system detailed in this study advanced noncontinuously hundreds of kilometres to the east and southeast into the adjacent marine basin where it intertongues with coeval Bearpaw Formation marine shale, and represents the regressive systems tract of this third-order sequence. These sandy and coaly strata have been referred to the Horseshoe Canyon Formation, St. Mary River Formation and Eastend Formation in the Plains of southern Alberta and Saskatchewan.

Upon beginning this study, it was immediately clear that previously defined stratigraphic nomenclature (based only on one outcrop area) was inadequate to describe the naturally occurring, and regionally extensive subdivisions of these strata, which result from tectonosedimentary controlling factors. In the study area, the primarily regressive Horseshoe Canyon Formation includes five, new, informal, mappable units of marginal-marine to nonmarine aspect, in ascending order: 1) Strathmore tongue – up to 111 m of thinly interbedded sandstone, siltstone and coal, present only in the subsurface; 2) Hoodoo tongue – up to 146 m of thinly interbedded sandstone, siltstone and abundant coal, including well-developed vertisols, gleysols and calcisols, paleoflow to the east-southeast; 3) Midland tongue – up to 181 m of thinly interbedded sandstone, siltstone and coal, less coaly than the Hoodoo, including vertisols, incipient gleysols and calcisols, paleoflow to the east-southeast; 4) Tolman tongue – up to 125 m of thinly interbedded green pedogenic siltstone and sandstone, with essentially no coal, including well-developed, stacked vertisols and calcisols, paleoflow to the east-southeast; and 5) Carbon tongue – up to 98 m of thickly interbedded sandstone, siltstone and coal, including vertisols, gleysols, calcisols and a distinct white sandstone spodosol at the top, paleoflow to the east. These members are separated by tongues of coeval Bearpaw Formation marine shaly deposits that extend from the basinal area of the southeast toward the northwest into this predominantly nonmarine sandy depositional system. This southeasterly depositional basin tilt is a continuation of that established during sedimentation of the underlying Dinosaur Park Formation of the Belly River Group (which represents the transgressive systems tract of this third-order sequence).

In regional subsurface cross-sections, the four, shaly, marine tongues and the five, sandy, nonmarine tongues together define five, coarsening-upward, shallowing-upward regressive cycles of regionally mappable extent, which were stacked in a progradational set extending progressively to the east and southeast through time. In the study area, each of these fourth-order cycles comprises a) a lower, thinner, marine-shale-dominated tongue that thins and pinches out (from the top) to the northwest (sourceward), and b) an upper, thicker, nonmarine sandstone- or coal-dominated tongue that thins and pinches out (from the base) to the southeast (basinward). In the area of intertonguing, basal boundaries of cycles are typically sharp and placed, for convenience, at a flooding surface where interpreted marine shale overlies coal. Through the time of Horseshoe Canyon Formation deposition, the locus of shoreline-related sandy deposition, and the maximum penetration of marine influence, shifted southeastward (basinward). This is clearly manifest as the seaward limit of sandy deposition of each succeeding cycle overlies and is located southeastward of the preceding one. The Horseshoe Canyon Formation thus represents overall, but noncontinuous regression. Maximum transgression occurred near the base of the lowest Bearpaw tongue (interpreted to reflect rapid subsidence and base level rise as a result of renewed thrust loading), whereas maximum regression toward the southeast is associated with the subaerial unconformity at the top of the Carbon tongue (top of the formation). A progressive trend in paleosol styles, from more humid types in the Strathmore to more arid types in the Tolman, suggests an overall drying climatic trend, followed by a return to more humid conditions in the Carbon tongue. Each fourth-order cycle is also a composite of several thinner, fifth-order, coarsening-upward regressive subunits that mimic the thinning and fining characteristics of the larger cycles. Several of these fifth-order subunits (included within the Hoodoo tongue, Cycle B) have been studied in detail by other authors at well-known outcrops near Willow Creek. They embody strata representing a variety of marginal-marine depositional environments and include northwest–southeast-trending channel and estuarine sandstones and northeast–southwest-trending shoreface sandstone. Similar facies and relationships can be expected in other tongues and subunits.

Strata of the Horseshoe Canyon Formation have significant potential for important hydrocarbon, coalbed methane, and groundwater resources that has not yet been adequately assessed. Conclusions reached in this study will aid in reducing risk in exploration and exploitation of these resources. Each newly identified tongue contains at least a few known shallow gas pools, although most discovered to date are small, low pressure and were found by serendipity. However, initial assessment suggested that there is potential for many additional pools of small to moderate size, primarily in northwest–southeast-trending channels and estuarine bodies and in northeast–southwest-trending shoreface-related sandstone reservoirs. The many, thick, near-surface coal seams of the Horseshoe Canyon present a new opportunity for methane extraction, as well as a source for gas in conventional reservoirs. Coals are especially well developed in association with flooding surfaces at the bases of Bearpaw marine tongues that separate sandy depositional tongues. These coals are known to have high vitrinite content, fracturing, porosity and permeability, and are currently being evaluated for commercial viability. Adjacent high-quality sandstone reservoirs may also increase the possibilities for economic exploitation. Likewise, strong flows of Na-rich, low S waters have been obtained from sandstone aquifers in the Horseshoe Canyon Formation and their correlatives in the adjacent Bearpaw Formation. Certain porous and permeable sandstone and coal aquifers, many fractured, provide substantial flows and represent the prime source of groundwater in some parts of Alberta. Detailed mapping of fourth-order cycles and fifth-order channel, shoreline and coal seam facies should elucidate greater potential and this groundwater may represent a relatively unstudied resource with increasing importance in the future.

SOMMAIRE

Afin de mieux comprendre la stratigraphie régionale, la sédimentologie et les ressources potentielles des strates sableuses du Campanien supérieur-Maastrichtien du sud de l'Alberta, on a étudié une série de coupes mesurées d'affleurements et de coupes transversales de puits avoisinants. Puisque ces strates n'ont été examinées que dans une seule zone d'affleurement très fréquentée et que leur subsurface a été peu étudiée, une partie de ce rapport présente une synthèse des renseignements figurant dans diverses publications antérieures afin d'établir un bon cadre de travail pour les interprétations suivantes. Dans le cadre de la présente étude, a) on tente de corréler et d'intégrer des données tirées d'affleurements et de diagraphies de puits exécutés à proximité afin de délimiter les tendances régionales en matière de sédimentation et d'établir une subdivision des strates plus facile à reconnaître; b) on présente les interprétations de l'architecture stratigraphique régionale, des lithofaciès et de la sédimentologie propres aux strates du Campanien tardif-Maastrichtien; c) on établit un cadre stratigraphique provisoire de portée régionale, en commençant par le secteur le plus distal d'interdigitation avec la Formation de Bearpaw contemporaine et en extrapolant jusqu'aux secteurs plus proximaux; et d) on évalue les ressources potentielles en hydrocarbures, en charbon et en eaux souterraines.

La succession de bassins d'avant-pays de premier ordre du Bassin sédimentaire de l'Ouest du Canada comprend un biseau composite de deuxième ordre à granoclassement inverse, qui s'amincit vers l'est et dont l'épaisseur peut atteindre 3,5 km. Ce biseau, dont l'âge s'échelonne du Campanien au Paléocène, représente l'étape finale de l'évolution de l'avant-pays. Une séquence de troisième ordre du Campanien tardif-Maastrichtien s'est accumulée sur la marge nord-ouest de l'important bras de mer intérieur de Bearpaw, à direction nord-sud, en même temps qu'a eu lieu une partie de la déformation associée à la collision entre le superterrane insulaire et le superterrane intermontagneux. Une partie de cette séquence a été examinée dans le cadre de la présente étude. Cette séquence de troisième ordre de Dinosaur Park-Bearpaw-Horseshoe Canyon est limitée par la discordance sous la Formation de Dinosaur Park, à la base, et par la discordance postérieure à la Formation de Horseshoe Canyon, au sommet. La surface d'inondation maximale, qui se trouve juste au-dessus du sommet du Groupe de Belly River, sépare le cortège transgressif (Dinosaur Park) du cortège régressif (Bearpaw-Horseshoe Canyon). Le système de progradation décrit dans la présente étude s'est avancé de manière discontinue sur des centaines de kilomètres à l'est et au sud-est jusque dans le bassin marin adjacent, où il est interdigité avec du shale marin contemporain de la Formation de Bearpaw; il représente la zone de cortèges régressifs de cette séquence de troisième ordre. Ces strates sableuses et charbonneuses ont été attribuées aux formations de Horseshoe Canyon, de St. Mary River et d'Eastend dans les plaines du sud de l'Alberta et en Saskatchewan.

Dès le début de la présente étude, il s'est avéré évident que la nomenclature stratigraphique préalablement définie (d'après une seule zone d'affleurement) ne suffisait pas à décrire les subdivisions naturelles de vaste étendue régionale de ces strates, qui sont le produit de facteurs limitatifs tectonosédimentaires. Dans la région à l'étude, la Formation de Horseshoe Canyon, qui est principalement régressive, comprend cinq nouvelles unités informelles d'aspect margino-marin à non marin qu'il est possible de cartographier. Par ordre ascendant, ces unités sont les suivantes : 1) la langue de Strathmore, comportant jusqu'à 111 m de grès, de siltstone et de charbon finement interstratifiés et présents seulement en subsurface; 2) la langue de Hoodoo, comportant jusqu'à 146 m de minces interstrates de grès, de siltstone et de charbon abondant, avec des vertisols, des gleysols et des calcisols bien développés, à paléo-écoulement vers l'est-sud-est; 3) la langue de Midland, comportant jusqu'à 181 m de minces interstrates de grès, de siltstone et de charbon (moins charbonneuse que la langue de Hoodoo), avec des vertisols, des calcisols et des gleysols naissants, à paléo-écoulement vers l'est-sud-est; 4) la langue de Tolman, comprenant jusqu'à 125 m de minces interstrates de grès et de siltstone pédogénétiques verts, presque sans charbon, avec des vertisols et des calcisols empilés bien développés, à paléo-écoulement vers l'est-sud-est; et 5) la langue de Carbon, comportant jusqu'à 98 m d'interstrates épaisses de grès, de siltstone et de charbon, avec des vertisols, des gleysols, des calcisols et, au sommet, un podzol de grès blanc distinctif, à paléo-écoulement vers l'est. Ces membres sont séparés les uns des autres par des langues formées de dépôts shaleux marins contemporains de la Formation de Bearpaw qui s'étendent vers le nord-ouest depuis la zone de bassin du sud-est jusque dans ce système de dépôt sableux principalement non marin. Ce basculement vers le sud-est du bassin sédimentaire représente une prolongation du basculement ayant commencé au cours de la sédimentation de la Formation de Dinosaur Park sous-jacente du Groupe de Belly River (qui représente le cortège transgressif de cette séquence de troisième ordre).

Dans des coupes transversales régionales de la subsurface, les quatre langues marines shaleuses et les cinq langues non marines sableuses représentent cinq cycles régressifs à granoclassement inverse qui attestent d'une diminution de la profondeur de l'eau vers le haut de la séquence et qui ont été empilés dans un faisceau de progradation qui s'est étendu progressivement vers l'est et vers le sud-est au fil du temps. Ces cycles régressifs peuvent être cartographiés à l'échelle régionale. Dans la région à l'étude, chacun de ces cycles de quatrième ordre comprend a) une langue inférieure plus mince, à prédominance de shale marin, qui s'amincit progressivement jusqu'à disparition (depuis le sommet) vers le nord-ouest (vers la source), et b) une langue supérieure plus épaisse, à prédominance de charbon ou de grès non marin, qui s'amincit progressivement jusqu'à disparition (depuis la base) vers le sud-est (vers le bassin). Dans la zone d'interdigitation, les limites inférieures des cycles sont généralement nettes et établies (à des fins pratiques) sur une surface d'inondation où du shale considéré comme marin recouvre du charbon. Pendant l'accumulation de la Formation de Horseshoe Canyon, le foyer de sédimentation sableuse associée au rivage ainsi que l'aire d'influence marine se sont déplacés vers le sud-est (vers le bassin), ce dont témoigne clairement la position de la limite (côté mer) de sédimentation sableuse de chaque cycle successif au-dessus et au sud-est de la précédente. La Formation de Horseshoe Canyon représente donc une régression globale mais discontinue. La transgression maximale s'est produite près de la base de la langue de

Bearpaw inférieure (ce qui refléterait une subsidence et une montée rapides du niveau de base attribuables à une réactivation des charges axiales). Par contre, la régression maximale vers le sud-est est associée à la discordance subaérienne qui se trouve au sommet de la langue de Carbon (sommet de la formation). La progression des types de paléosol depuis des types plus humides, dans la langue de Strathmore, à des types plus arides, dans la langue de Tolman, laisse supposer qu'un assèchement général du climat a été suivi par un retour à des conditions plus humides dans la langue de Carbon. Chaque cycle de quatrième ordre renferme également un ensemble de plusieurs sous-unités régressives plus minces de cinquième ordre, à granoclassement inverse, qui reproduisent les tendances en matière d'amincissement et de granodécroissance des cycles plus gros. Plusieurs de ces sous-unités de cinquième ordre (incluses dans le cycle B de la langue de Hoodoo) ont été étudiées en détail par d'autres auteurs à des affleurements bien connus près du ruisseau Willow. Elles comportent des strates qui représentent une gamme de milieux de sédimentation margino-marins, y compris des grès d'estuaire et de chenal à direction nord-ouest–sud-est et du grès d'avant-plage à direction nord-est–sud-ouest. On peut s'attendre à trouver des faciès et des relations similaires dans d'autres langues et sous-unités.

Les strates de la Formation de Horseshoe Canyon contiennent d'importantes ressources potentielles en hydrocarbures, en méthane des gisements de charbon et en eaux souterraines, ressources que l'on n'a pas encore suffisamment évaluées. Les conclusions formulées dans la présente étude permettront de réduire les risques associés à l'exploration et à l'exploitation de ces ressources. Chaque langue nouvellement reconnue renferme au moins quelques gisements de gaz naturel peu profonds, bien que la plupart de ceux qui ont été découverts jusqu'à maintenant soient petits, présentent une pression peu élevée et aient été trouvés par hasard. Cependant, une première évaluation a permis de croire qu'il existe nombre d'autres gisements de gaz naturel de petite à moyenne dimension, principalement dans des strates de chenal et d'estuaire à direction nord-ouest–sud-est et dans des réservoirs de grès d'avant-plage à direction nord-est–sud-ouest. Les nombreux filons houillers épais et proches de la surface de la Formation de Horseshoe Canyon pourraient, d'une part, être exploités pour en extraire du méthane et, d'autre part, renfermer du gaz naturel dans des réservoirs classiques. Les charbons sont particulièrement bien développés en association avec les surfaces d'inondation trouvées à la base des langues marines de Bearpaw qui séparent les langues sédimentations sableuses. On évalue présentement le potentiel commercial de ces charbons, qui sont connus pour leur forte teneur en vitrinite, leur fracturation, leur porosité et leur perméabilité. La présence de réservoirs de grès adjacents de haute qualité pourrait aussi accroître la possibilité d'une exploitation économique. Pareillement, la Formation de Horseshoe Canyon et la Formation de Bearpaw adjacente renferment des aquifères de grès dans lesquels s'écoulent avec force des eaux riches en Na et pauvres en S. Une quantité élevée d'eau s'écoule dans certains aquifères de charbon et de grès poreux, perméables et, dans nombre de cas, fracturés, et ces derniers constituent une importante source d'eaux souterraines dans certaines parties de l'Alberta. La cartographie détaillée des cycles de quatrième ordre et des faciès de filon houiller, de rivage et de chenal de cinquième ordre devrait permettre de découvrir un potentiel accru; ces cycles pourraient représenter des ressources relativement peu étudiées dont l'importance s'accroîtra dans l'avenir.

INTRODUCTION

Rationale and objectives

The sandstone-dominated upper Campanian–Maastrichtian strata of the southern Alberta Plains have been termed the "Edmonton" Group for more than a century, although the exposures at the city of Edmonton are poor at best. The part of the Edmonton Group known as the Horseshoe Canyon Formation (Irish, 1970) is exposed in excellent outcrops along the Red Deer River around Drumheller (the famous "Drumheller Badlands"), is logged in thousands of petroleum wells in west-central Alberta and contains significant hydrocarbon resources, both discovered and potential (Hamblin and Lee, 1997). Dozens of small pools in the sandstone produce gas (Hamblin and Lee, 1997). It is also emerging as a major source of coalbed methane, and may provide significant future groundwater resources. The Horseshoe Canyon Formation sandy deposits and the underlying and intertonguing Bearpaw Formation marine shale have long been recognized as representing a generally diachronous, shoreline-related facies set. Gibson (1977) provided an excellent basic view of the stratigraphy, sedimentology and coal seams of the clastic wedge in the Red Deer River valley. However, aside from the intensively studied lower 60 m in the Willow Creek-East Coulee area, the unit has received little modern stratigraphic analysis. In particular, synthesis of internal regional relationships, the melding of surface and subsurface data and the presentation of paleocurrent data have been lacking, and hence there is no consistent regionally applicable subdivision, subsurface mapping, or appreciation of reservoir geometries, exploration concepts and tectono-stratigraphic significance.

The objectives of this report are eight-fold: 1) to provide a brief, but necessary synthesis of the literature and extant concepts for the Horseshoe Canyon Formation strata, 2) to attempt a regional stratigraphic analysis integrating both outcrop measured sections and subsurface log correlation, 3) to formally revise the upper boundary of the Horseshoe Canyon Formation to better reflect more recent data and understanding, 4) to delineate a more recognizable and useful informal stratigraphic subdivision for these strata that will prove more useful than the current terminology and may be formalized later, 5) to briefly describe and interpret the general facies that recur throughout the formation, 6) to establish a regional stratigraphic framework based on the intertonguing of informal marine and nonmarine units, 7) to suggest some inferences regarding the creation and filling of accommodation space both areally and regionally, and 8) to review the current state of knowledge of enclosed resources and examine the potential for the future.

Study area, measured sections, and subsurface database

In order to more fully understand the regional stratigraphy, sedimentology, and hydrocarbon and coalbed methane potential of the Upper Cretaceous (upper Campanian–Maastrichtian) Horseshoe Canyon Formation strata of south-central Alberta, a field and subsurface program was initiated. A total of 39 outcrop measured sections, one major core, and about 300 wells with geophysical logs were studied, primarily from the area enclosed within Twp. 20–40, Rge. 15–30W4 (Fig. 1) (see Appendix I for detailed outcrop locations; Appendix II for subsurface well locations and tops). The region was chosen because it includes excellent (but little-studied) outcrops in a well-known area, adequate subsurface control close to outcrops, one of the few continuous cores of Campanian–Maastrichtian deposits, and the crucial interfingering relationship of marine and nonmarine strata.

Standard field techniques were used and detailed sedimentological observations recorded and paleocurrent indicators measured. Outcrops measured are concentrated along the famous Red Deer River valley (where there is excellent lateral exposure of flat-lying strata, stretching over several hundred kilometres of lateral river valley distance), and the little-studied adjacent valleys of Rosebud River and Kneehills Creek (Fig. 2). These outcrop areas lie in Twp. 26–34, Rge. 17–23W4. Although this area is familiar to geologists and laypersons alike, only the lowermost portion of the strata in question has ever been studied in detail, and then only in a limited geographic location. In effect, 90 per cent of the available information has been underutilized. The core is from a well located about 40 km to the southwest (downdip) of the main outcrop area in Twp. 25, Rge. 25W4. Because the regional dip in this area is less than 1°, no single outcrop exposes the entire formation in vertical succession. In fact, it is necessary to examine at least 100 km of lateral exposure to study the entire unit. Over this paleogeographic distance many facies changes occur, hence the importance of incorporating the long vertical sections afforded by the subsurface data. A network of 21 west-east subsurface log cross-sections (one per Township), comprising a total of 256 wells, was constructed and correlated to define meaningful regional stratigraphic patterns that can be matched to the outcrop observations. The well spacing was approximately one well per Township/Range (see Appendix II for locations and tops).

A persistent problem occurs in attempting to utilize subsurface data for a shallow unit in an area close to outcrop: the potential lack of wells with geophysical

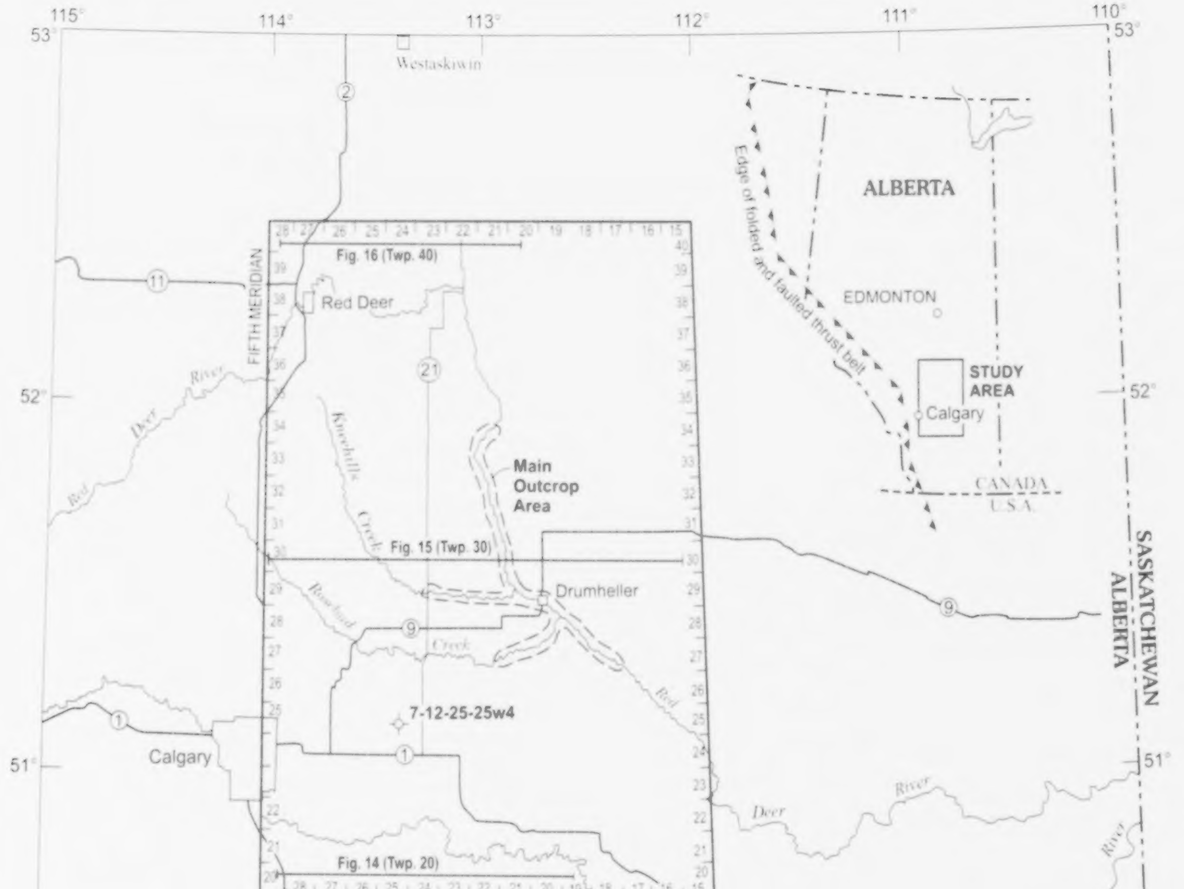

Figure 1. *Study area, outcrop area, subsurface cross-sections, and core utilized in this study.*

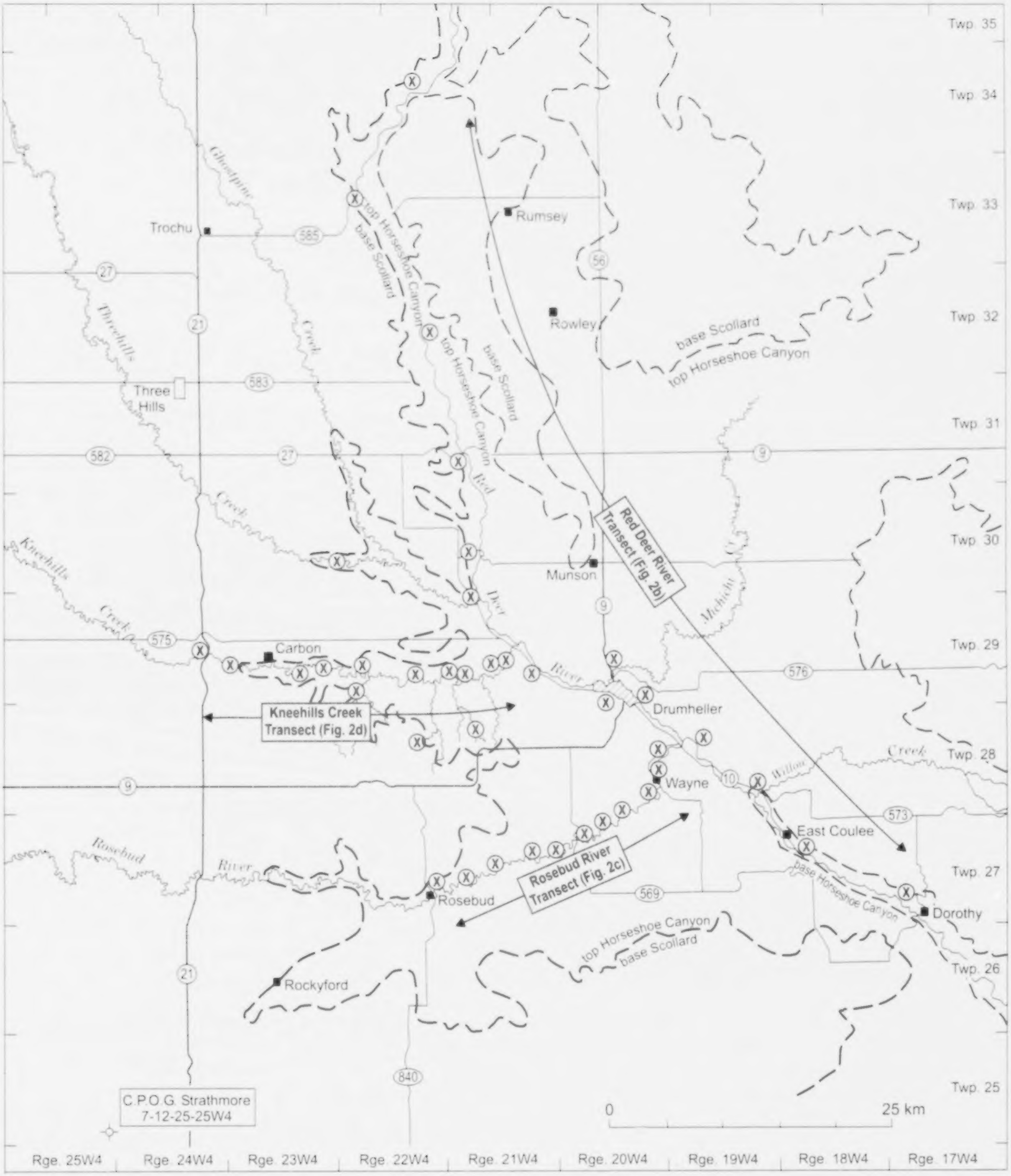

Figure 2a. *Outcrop and core measured-section locations with outcrop base and top of Horseshoe Canyon strata shown.*

logging *shallow enough* to give adequate coverage of the unit in question. In many wells, the strata studied are behind surface casing and thus inadequately logged. Consequently, careful choice of wells with the shallowest logging intervals was a crucial, and time-consuming, preliminary step. However, data relevant to the uppermost part of the strata is inevitably and progressively missing toward the eastern edge of the study area where Maastrichtian strata rise toward surface outcrop.

Correlations for each well were made by referring to all surrounding wells on adjacent cross-sections, and resulted in the definition of new informal member-rank units of mappable regional extent, and the regional intertonguing relationship between the Bearpaw marine shale and the Horseshoe Canyon nonmarine deposits. Tops and isopach values are compiled in Appendix II and were used to construct maps of each unit. Three simplified cross-sections (total of 19 wells) are included here for illustration.

The outcrop sections represent a cumulative total of 2275 m of measured thickness, individually ranging from 16 to 119 m. The core includes a nearly complete section of the strata in question, measuring 350 m thick (see Hamblin, 1998c). Although these flat-lying strata are mapped over a considerable area of southwestern Alberta (Fig. 2), outcrop quality is good only in the river valleys included here. To the south, the partly correlative St. Mary River Formation is well exposed in similar valleys but is not included in the current study (see Hamblin, 1998a, b, d).

A significant body of paleocurrent data was collected during this study, the largest so far from these strata (see Appendix I for raw data). These data proved useful in delineating sediment source areas and regional dispersal patterns. A total of 575 measurements were taken, of which 360 represent data from trough-crossbeds, while the rest are primarily from ripple crosslamination (82), and inclined surfaces (133). In addition, 64 measurements (primarily

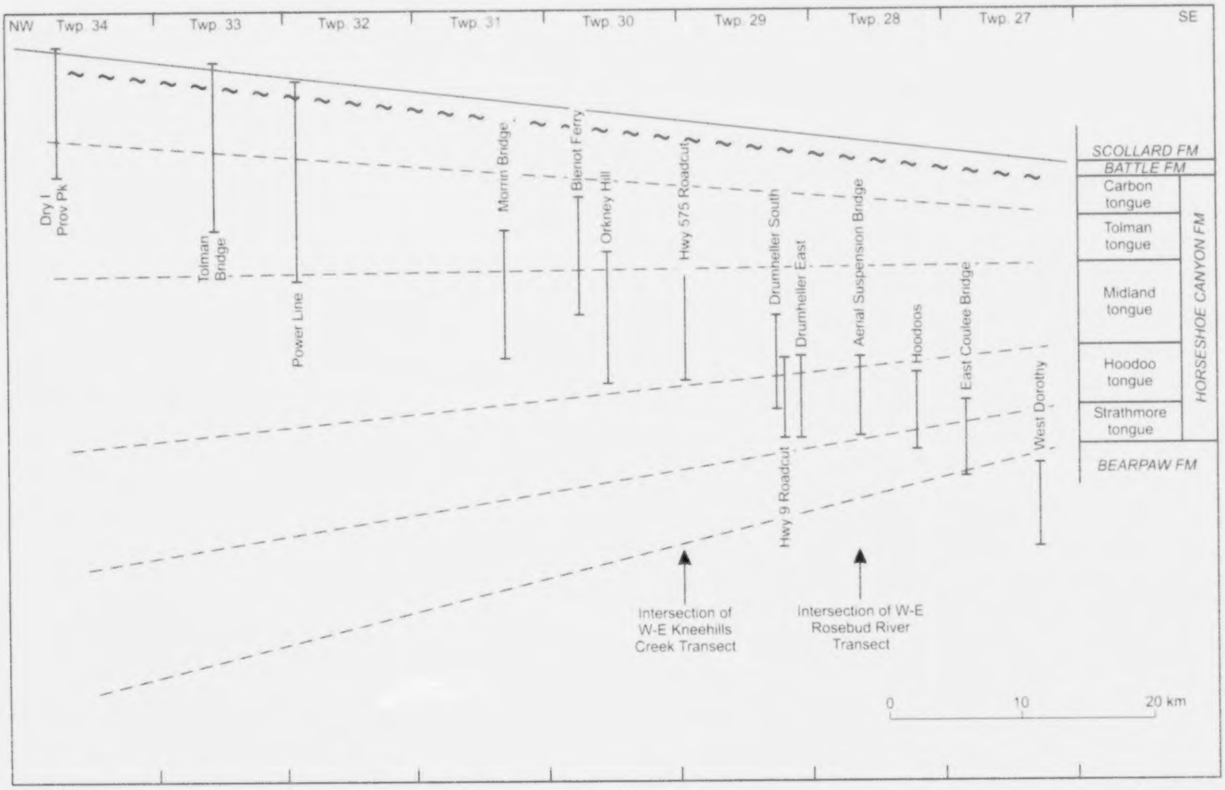

Figure 2b. Outcrop transect along Red Deer River (across structural strike and along depositional dip).

trough-crossbeds) were obtained from the overlying basal Scollard Formation, the first such body of data from this unit.

New informal stratigraphic nomenclature and minor revision

During compilation of previous literature by other workers, and synthesis of my own sedimentological observations, it became clear that a significant regional unconformity exists between strata of the Whitemud and Battle formations. Therefore, I herein suggest that this recently recognized, but generally unemphasized, unconformity be utilized as the top of the Horseshoe Canyon Formation, with the Whitemud being re-interpreted as a pedogenically-altered zone beneath this surface, and the Battle Formation being considered as part of the overlying sequence. This requires a minor revision to the formal definition of the upper contact of the Horseshoe Canyon Formation, and downgrading of the Whitemud from formal formation to informal unit.

In addition, during this study it became clear that the previously defined formations ("Horseshoe Canyon", "Whitemud", "Battle", "Scollard") of the Edmonton Group do not adequately describe the natural internal organization of these rocks. On the basis of new data presented here, five new, informal, member-scale lithostratigraphic subdivisions within the previously defined Horseshoe Canyon Formation are recognized. For these units, most requirements for formal definition can be met with the current data, except the crucial criterion of defining and describing boundaries that can be consistently traced over large distances in outcrop and subsurface data sets, as set out in the North American Commission on Stratigraphic Nomenclature (1983) rules. This deficiency in boundary definition, common even in many units formally defined in the past in this basin, eliminates the possibility of formally defining subunits within the Horseshoe Canyon Formation with the information available now.

Therefore, I have suggested informal units ("tongues"), which I hope will be descriptive, usable, helpful and eventually formalized if they prove functional and when appropriate data are collected. The descriptions of these units supplied here include most of the information required in formal definitions according to the North American Stratigraphic Code (NACSN, 1983) and will form the basis for further study. In ascending order these informal subdivisions are the East Coulee tongue, Hoodoo tongue,

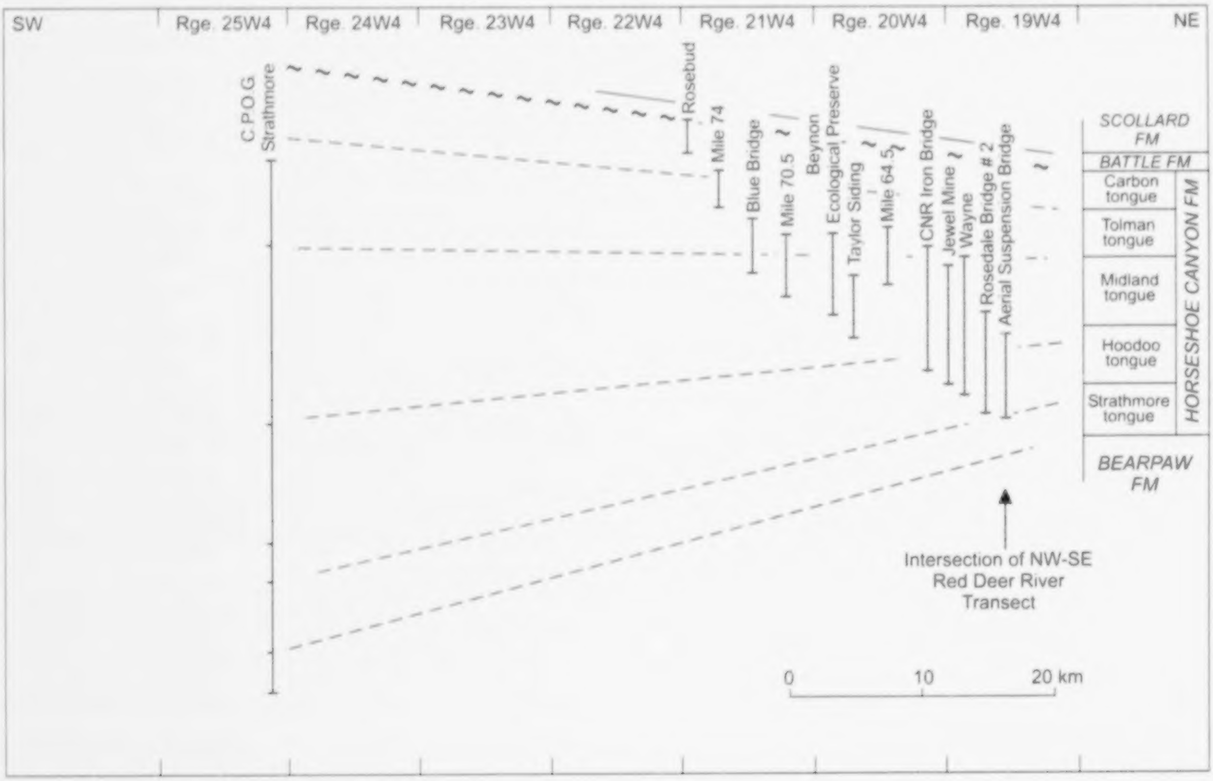

Figure 2c. *Outcrop transect along Rosebud River (along structural dip and across depositional strike).*

Midland tongue, Tolman tongue and Carbon tongue. Of these, only the Tolman has previously been described (in part) as an informal member-scale unit.

Tectono-sedimentary analysis of basin-fill successions

The conclusions reached in this study are based on the treatment of these Upper Cretaceous strata of southern Alberta as a sedimentary succession of diachronous deposits that partly filled a foreland basin. The style and spatial arrangement of facies reflect the nature and distribution of sedimentary environments, which in turn result from regional tectonic activity before and during deposition. These facies can be used to interpret the sedimentary and structural evolution of the basin through time.

This study deals with a considerable stratigraphic thickness of rocks present over a large area (which have not previously been well-studied), synthesized into a stratigraphic framework within which further studies can be organized. Stratigraphic and sedimentological analysis at two scales is involved: 1) the lithofacies and paleocurrents observed in outcrops and cores, which reflect local depositional environments; and 2) the depositional systems observed through more regional correlation of facies and sequences across the outcrop belt and subsurface cross-sections, which reflect interaction of subsidence and sediment supply. The result is a four-dimensional tectono-stratigraphic sedimentation model for the unit.

One of the first steps in the process was to attempt regional subsurface correlation of the previously designated stratigraphic units by extrapolating westward and downdip from the outcrop exposures of the Red Deer River valley. It immediately became obvious that the stratigraphic nomenclature established for the Horseshoe Canyon Formation at those scattered outcrops is inadequate for regional use, and in fact, completely masks the real and more practical subdivisions that are more obvious on geophysical logs covering the entire interval over large areas. This required a more logical subdivision of identifiable units, and the demonstration of these new units is a prime focus of this study.

Viewing these strata as a large-scale three-dimensional package of facies assemblages and depositional-stratigraphic sequences allows interpretations of paleogeography, depositional environments and vertical and lateral depositional patterns. The result is a tectono-

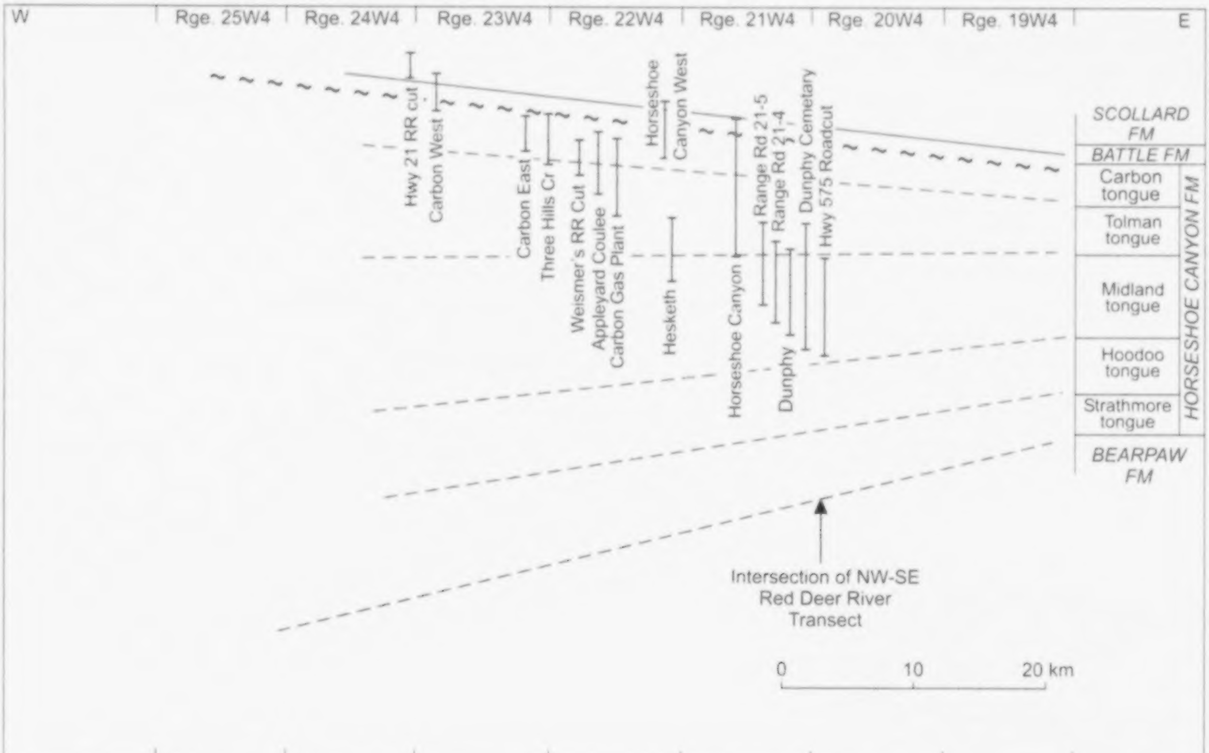

Figure 2d. Outcrop transect along Kneehills Creek (along structural dip and across depositional strike).

sedimentary basin-fill analogue, the aim of which is understanding the organization and significance of the depositional units comprising the succession. An analogue of this type forms the framework for future research because it involves a systematic approach to understanding the basic controls on the sedimentary characteristics of a unit. By identifying the characteristics of the tectono-sedimentary basin-fill model it may be possible to construct local hydrocarbon, coal, and groundwater deposit models.

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GENERAL TECTONIC AND DEPOSITIONAL SETTING

Regional foreland basin setting

In the Western Canada Sedimentary Basin (WCSB) the first-order foreland basin succession is the second of two, major, eastward-thinning wedges. It is approximately equivalent to the Zuni Sequence of Sloss (1963), and is a direct result of the evolution of the Canadian Cordillera during Jurassic to Paleocene time (Porter et al., 1982). A foreland basin is an asymmetrical sedimentary basin that develops between a deforming mountain front and the adjacent craton, where a great volume of orogen-derived sediment can accumulate in an active tectonic setting (Allen et al., 1986). It forms by downward flexure of the lithosphere in response to thrust loading at the convergent margin (Beaumont, 1981).

The Canadian Cordillera consists of a tectonic collage of allocthonous terranes (Monger, 1989). Collisional accretion of microcontinents to the western margin of ancient North America compressed and detached the underlying Paleozoic miogeoclinal wedge, and telescoped and translated these strata as imbricate thrust sheets to form the thickened orogenic belt (Porter et al., 1982; Price, 1994). This thrust sheet load flexed the crust to form a deeply subsiding asymmetrical foredeep, which migrated in front of the advancing thrust stack, and provided the source of detritus deposited in that foredeep (Beaumont, 1981; Price, 1994). This led to a dramatic reversal of sediment dispersal, from generally westward off the craton, to generally eastward off the orogen as the miogeoclinal and earlier molassic strata were cannibalized. As a result, an enormous volume of synorogenic shallow-marine and nonmarine sediments were deposited in asymmetrical, generally regressive clastic wedges (Leckie and Smith, 1993). Stratigraphic sequences in foreland basins are clearly controlled by regional tectonism, as evidenced by variation in sediment source, depositional regime, and uplift and subsidence patterns between successive sequences (Embry, 1990; Miall, 1991; Eberth and Hamblin, 1993; Hamblin, 1997).

Laramide Orogeny and basin infill

In mid-Cretaceous time, a change from orthogonal to oblique northward convergence caused western parts of the Cordillera to be displaced hundreds of kilometres to the north (Monger, 1989). Late Cretaceous (Turonian–Cenomanian) docking of the oceanic Insular Superterrane (Alexander-Wrangellia Terranes), and others, (Monger, 1989; Cant and Stockmal, 1989; Stockmal et al., 1993; Price, 1994) led to overthrusting of supracrustal rocks, rapidly intensifying tectonic loading, foredeep subsidence (creating accommodation space), and cannibalization of previous deposits. This resulted in rapid deposition of a series of generally regressive wedges of marine to nonmarine synorogenic molassic sediments from the Campanian to the Paleocene (Jerzykiewicz, 1985). This second-order composite coarsening-upward succession, up to 2.5 km thick, was deposited over 20 to 25 million years (sedimentation rate of about 175m/Ma) and represents the final stage of foreland evolution (Porter et al., 1982) and the last portion of the Zuni Sequence of Sloss (1963).

Cant and Stockmal (1989) and Chamberlain et al. (1989) noted the typical lag time between the increase in subsidence and the increase in sediment supply (here, up to 20 Ma between Superterrane docking and the appearance of coarse clastic detritus in the preserved portion of the foreland (Underschultz and Erdmer, 1991), creating generally coarsening-upward successions. This last portion of the Zuni Sequence (Sloss, 1963; Porter et al., 1982) represents an eastward-thinning wedge that extended into Manitoba (Taylor et al., 1964) but was later partially eroded after thrusting ceased and late-orogenic crustal extension began in Eocene time (Monger, 1989), leaving only erosional remnants over the Plains. Environments of deposition are generally nonmarine to the west and marine to the east (where preserved) and characterized by successive transgressive-regressive cycles (Leckie and Smith, 1993; Dawson et al., 1994). Subsidence and sedimentation rates relate directly to geographically limited tectonic loading and creation of accommodation space, and resulting sediment dispersal patterns.

Regional Upper Cretaceous–Tertiary internal stratigraphy

The second-order composite portion of the Zuni Sequence (Sloss, 1963; Porter et al., 1982) in the Plains (termed the "post-Colorado" section) represents an eastward-thinning prism originally up to 2.5 km thick, or more, which extended into Manitoba (Dawson et al., 1994). It was later partly eroded as crustal extension began in the Eocene (Monger, 1989; Price, 1994). Probably no major arches were active (although Lorenz, 1982, suggested that uplift of the Sweetgrass Arch was related to Laramide thrusting) and most sediment was supplied through cannibalization of earlier Paleozoic and Mesozoic strata from the emerging Rockies (Rahmani and Lerbekmo, 1975; Porter et al., 1982; Stott, 1984; Jerzykiewicz, 1985; Mack and Jerzykiewicz, 1989; Price, 1994).

The post-Colorado succession is an overall coarsening-upward succession (Jerzykiewicz, 1985). At least five, major, sandy clastic wedges related to orogenic pulses are present, representing infill of the foreland basin controlled by variable rates of tectonic subsidence (Jerzykiewicz, 1985; Mack and Jerzykiewicz, 1989). Jerzykiewicz and Labonte (1991) and Leckie and Smith (1993) noted that prevailing drainage in the proximal part of the foreland is perpendicular to the basin axis in overfilled phases and parallel to the basin axis in underfilled phases.

A north-south-trending broad inland seaway existed between the Canadian Shield and the active Cordilleran belt (Stott, 1984) stretching from the Arctic to the Gulf of Mexico, generally with north-south, northwest-southeast or northeast-southwest shoreline trends (Rosenthal, 1984). Environments of deposition are generally nonmarine to the west intertonguing with marine to the east (where preserved) (Leckie and Smith, 1993; Dawson et al., 1994). These reflect a series of stacked transgressive-regressive cycles (Dawson et al., 1994), with less marine influence through time. The climatic conditions were warm-temperate to subtropical, and semiarid to increasingly humid northward (Jerzykiewicz and Sweet, 1988).

The strata of this second-order succession are subdivided into five main sandstone-dominated depositional assemblages (Fig. 3, 4):

1. Lower Campanian Milk River Formation (and equivalents) – shallow-marine and shoreline, with minor fluvial deposits;
2. Middle to upper Campanian Belly River (Judith River) Group (and equivalents) –fluvial, shoreline, estuarine and shallow-marine deposits;
3. Upper Campanian to upper Maastrichtian Horseshoe Canyon Formation (and equivalents) – fluvial, shoreline and shallow-marine deposits;
4. Upper Maastrichtian to Lower Paleocene Scollard Formation (and equivalents) –fluvial deposits;
5. Middle to Upper Paleocene Paskapoo Formation (and equivalents) – fluvial deposits.

These sandstone-dominated depositional assemblages form the primarily regressive, nonmarine portions of third-order successions and are separated by marine tongues (between lower wedges) and regional unconformities (between upper wedges). Each successive clastic wedge is dominated more by continental facies and less by marine facies. Within earlier assemblages, higher order transgressive-regressive cycles are very important on local scales, and were likely controlled by variations in the interaction of tectonic subsidence and sediment supply.

The upper Campanian–Maastrichtian sequence in the WCSB context

The Dinosaur Park, Bearpaw, Horseshoe Canyon, St. Mary River, and Eastend formations of the Plains collectively represent a vast east- or southeast-thinning wedge of generally nonmarine to marginal-marine sediments deposited along the western or northwestern margin of a subsiding marine seaway (represented by the Bearpaw Formation), which may have stretched from the Arctic to the Atlantic to the Gulf of Mexico (Gibson, 1977; Lerand, 1983). The deposition of this third-order transgressive-regressive sequence was synchronous with part of the displacement and deformation associated with the collision of Insular Superterrane with Intermontane Superterrane, which produced the Rocky Mountain Thrust and Fold Belt and the Foreland Basin (Price, 1994). At the time of deposition, the developing Cordillera was several hundred kilometres west of southern Alberta Plains and dominated by a regime of right-lateral transpression (Price, 1994). There may have been weak pulsatory uplift on the Sweetgrass Arch with minor flexure of the Interior Basin (Lorenz, 1982; Caldwell, 1983; Catuneanu and Sweet, 1999).

A major, north-south, broad inland seaway existed between the Canadian Shield and the active Cordilleran belt (Stott, 1984) stretching from the Arctic to the Gulf of Mexico, generally with north-south or northwest-southeast

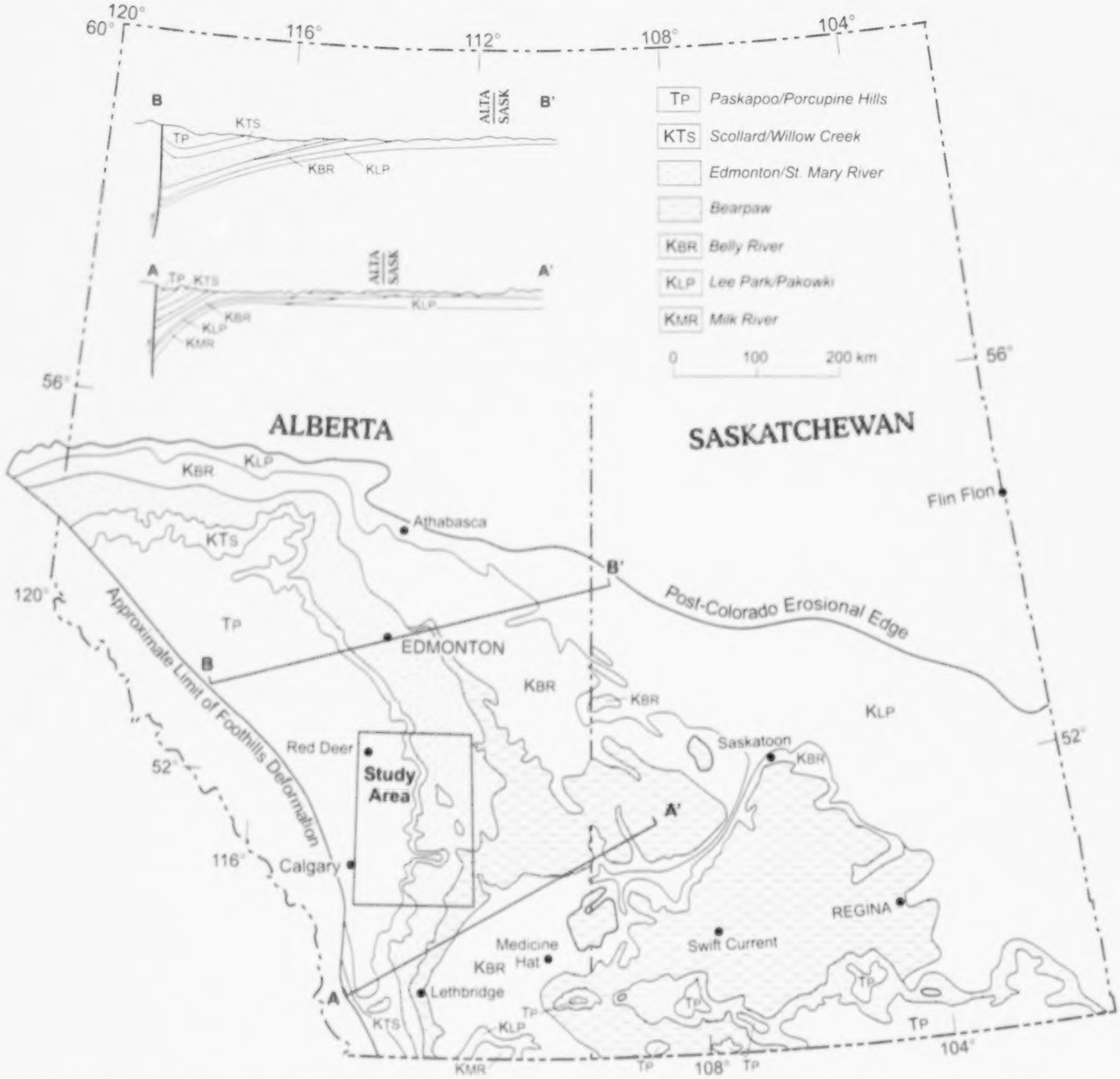


__Figure 3.__ Major nonmarine clastic wedges and marine shale units included in second-order post-Colorado Sequence. Bearpaw-Horseshoe Canyon Succession (Campanian–Maastrichtian) highlighted.

shoreline trends (except for west-east trends in southernmost Alberta) (Rosenthal, 1984). Little detritus from the western Intermontane Belt was carried to the foreland because of the intervening uplifted Omineca Belt which acted as a drainage divide and sediment source (Leckie, 1989; Mack and Jerzykiewicz, 1989). The Bearpaw Cycle of Weimer (1960) lasted about 5 Ma and included the last major marine transgression preserved in the record. It was followed by an increase in sediment supply and volcanism that overwhelmed basin subsidence, allowing eastward progradation of the nonmarine wedge (Lerand, 1983). Initial rapid Bearpaw marine transgression apparently was synchronous with, and related to, tectonically induced subsidence due to movement on major thrusts (particularly the Lewis Thrust) and tectonic loading (Stockmal et al., 2001). It was diachronous in southwest Saskatchewan and extended to the northwest to somewhat beyond the Edmonton and Pembina area, as well as north of Peace River Arch (Shepheard and Hills, 1970; Stelck et al., 1976; McCabe et al., 1986; Nadon, 1988).

The Bearpaw Formation, dominated by marine shale, thins to the west and north, but thickens to the east and south (Link and Childerhose, 1931) at the expense of the

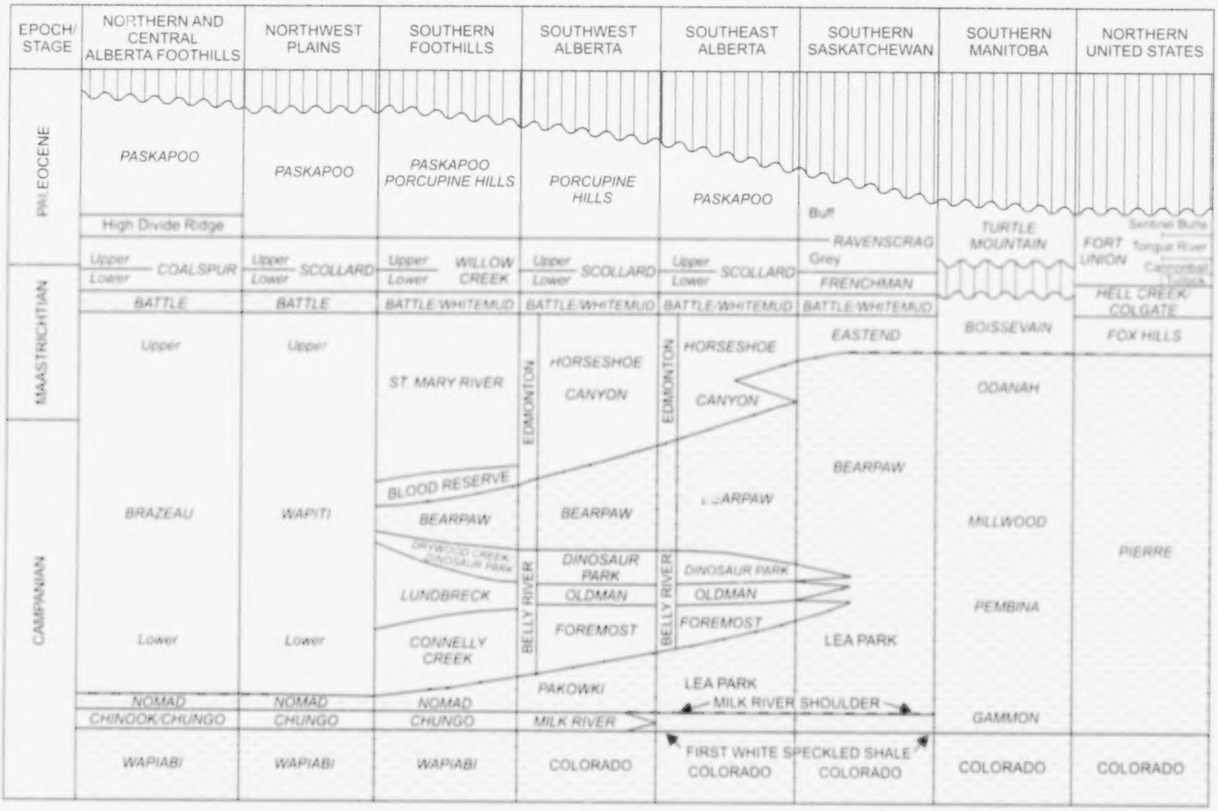


***Figure 4**. Simplified correlation chart for post-Colorado strata in WCSB.*

under- and overlying nonmarine prisms to become part of the Riding Mountain and Pierre formations (Caldwell, 1968; Shepheard and Hills, 1970; Stelck et al., 1976) (Fig. 5). There are several sandy members in southern Alberta and Saskatchewan (Link and Childerhose, 1931; Clark, 1931; Caldwell, 1968). After isostatic relaxation and uplift, the subsequent rapid increase in sediment supply allowed progradation of the nonmarine clastic wedge and concomitant rapid eastward withdrawal of the Bearpaw sea, first from central Alberta, then from southwestern Alberta and finally from southeastern Alberta and Saskatchewan (Shepheard and Hills, 1970; Rahmani and Schmidt, 1975; McCabe et al., 1986; Nadon, 1988). The resultant complex intertonguing of Bearpaw marine and Horseshoe Canyon shoreline and nonmarine sediments, characteristic of the present study area, represents the beginning of the major regressive phase with many minor, but widespread, transgressive pulses. This created a transitional marine–nonmarine diachronous contact, with variable lithologies, during the late Campanian–Maastrichtian (Link and Childerhose, 1931; Wall et al., 1971; Shepheard, 1978; McCabe et al., 1986).

The Horseshoe Canyon-St. Mary River-Eastend fluviodeltaic clastic wedge of complexly interfingering fresh to brackish and nonmarine facies, thickens greatly to the west (including all portions of the wedge) (Elliot, 1960; Yurko, 1975; Gibson, 1977) (Fig. 6). The wedge is characterized by great lateral and vertical variability in facies, general fine grain size, abundant thin coals, and abundant bentonites (Allan and Sanderson, 1945; Havard, 1971). The lower portion has the sedimentary and faunal characteristics of lower delta plain deposits with distributary channel, barrier island and backbarrier lagoon environments (Gibson, 1977), and deposition related to an embayed shoreline in estuarine and barrier island complexes (Rahmani, 1983). The shorelines are oriented west-southwest–east-northeast, with open sea to the southeast at Drumheller, and Rahmani (1983) suggested that the overall progradational trend was punctuated by four, rapid, minor marine transgressions within the lower 50 m of transitional stratigraphy. As described below, marine transgressions of much more regional extent and significance are also present in the lower half of this wedge.

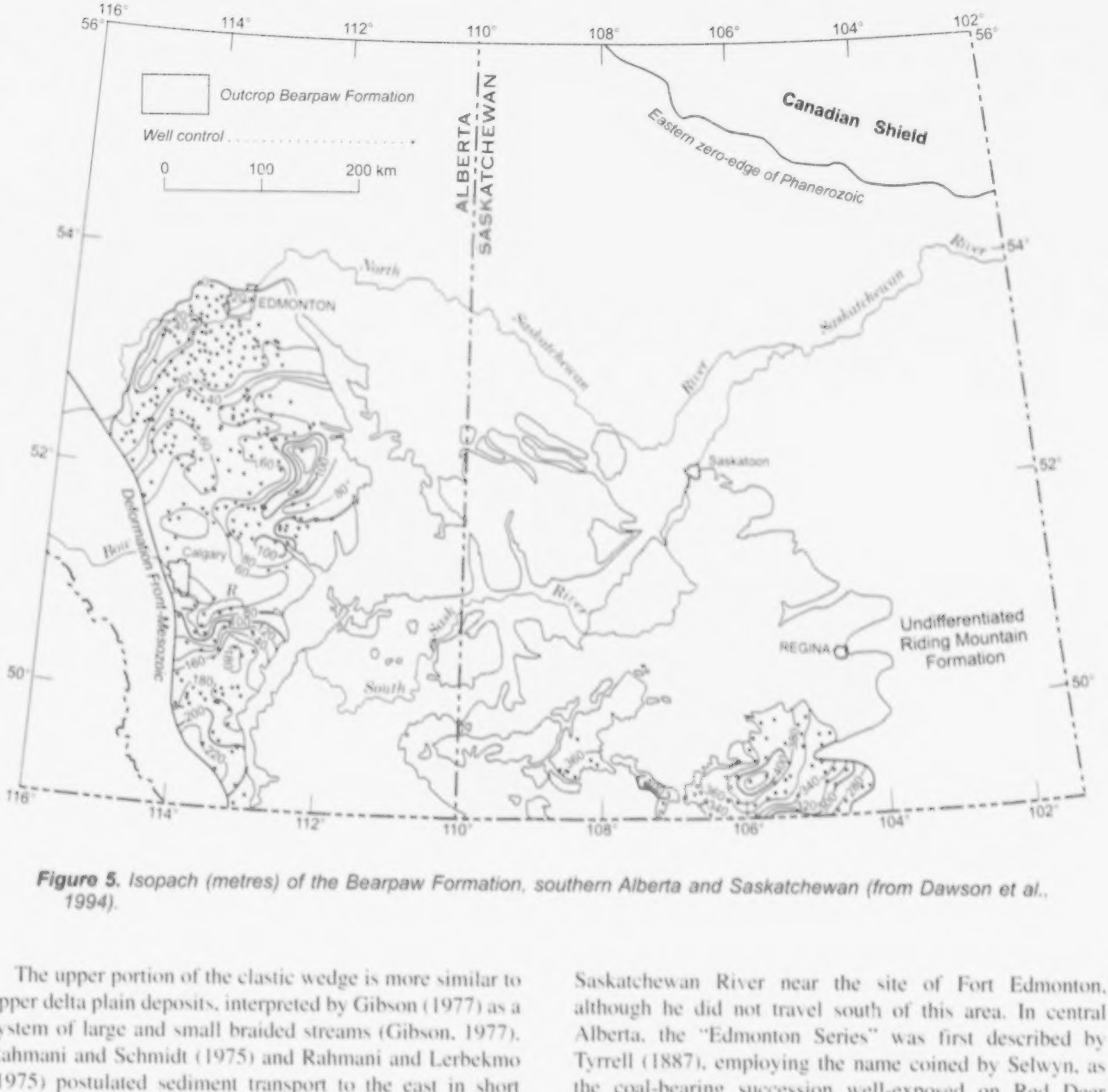


Figure 5. Isopach (metres) of the Bearpaw Formation, southern Alberta and Saskatchewan (from Dawson et al., 1994).

The upper portion of the clastic wedge is more similar to upper delta plain deposits, interpreted by Gibson (1977) as a system of large and small braided streams (Gibson, 1977). Rahmani and Schmidt (1975) and Rahmani and Lerbekmo (1975) postulated sediment transport to the east in short transverse drainage patterns that then connected to basinwide northwest to southeast longitudinal drainage in the Plains from a positive source area in northern and central B.C. Penecontemporaneous volcanism was prominent, as indicated by the presence of numerous bentonites and high montmorillonite clay content.

HORSESHOE CANYON FORMATION: STRATIGRAPHIC SETTING AND REVISION

Previous work (Fig. 7)

Selwyn (1874) first used the term "Edmonton" to describe coal-bearing Upper Cretaceous strata along the North Saskatchewan River near the site of Fort Edmonton, although he did not travel south of this area. In central Alberta, the "Edmonton Series" was first described by Tyrrell (1887), employing the name coined by Selwyn, as the coal-bearing succession well-exposed on Red Deer River between the Bearpaw marine shale and the Paskapoo sandstone (Williams and Dyer, 1930; Glass, 1990). Later referred to as the Edmonton Group, this unit has a gradational base, a sharp disconformable top, correlates with the upper Wapiti, upper Brazeau, and St. Mary River formations of the west and north, and the Eastend and Frenchman formations of the southeast (Glass, 1990), and comprises several formations. Since the 19th century, most outcrop studies of these strata have been conducted along the Red Deer River valley.

The initial subdivision of the Edmonton Group by Allan and Sanderson (1945) from studies of outcrops in the Red Deer River valley, included 1) Lower Edmonton, from the Bearpaw Formation to the top of the conspicuous

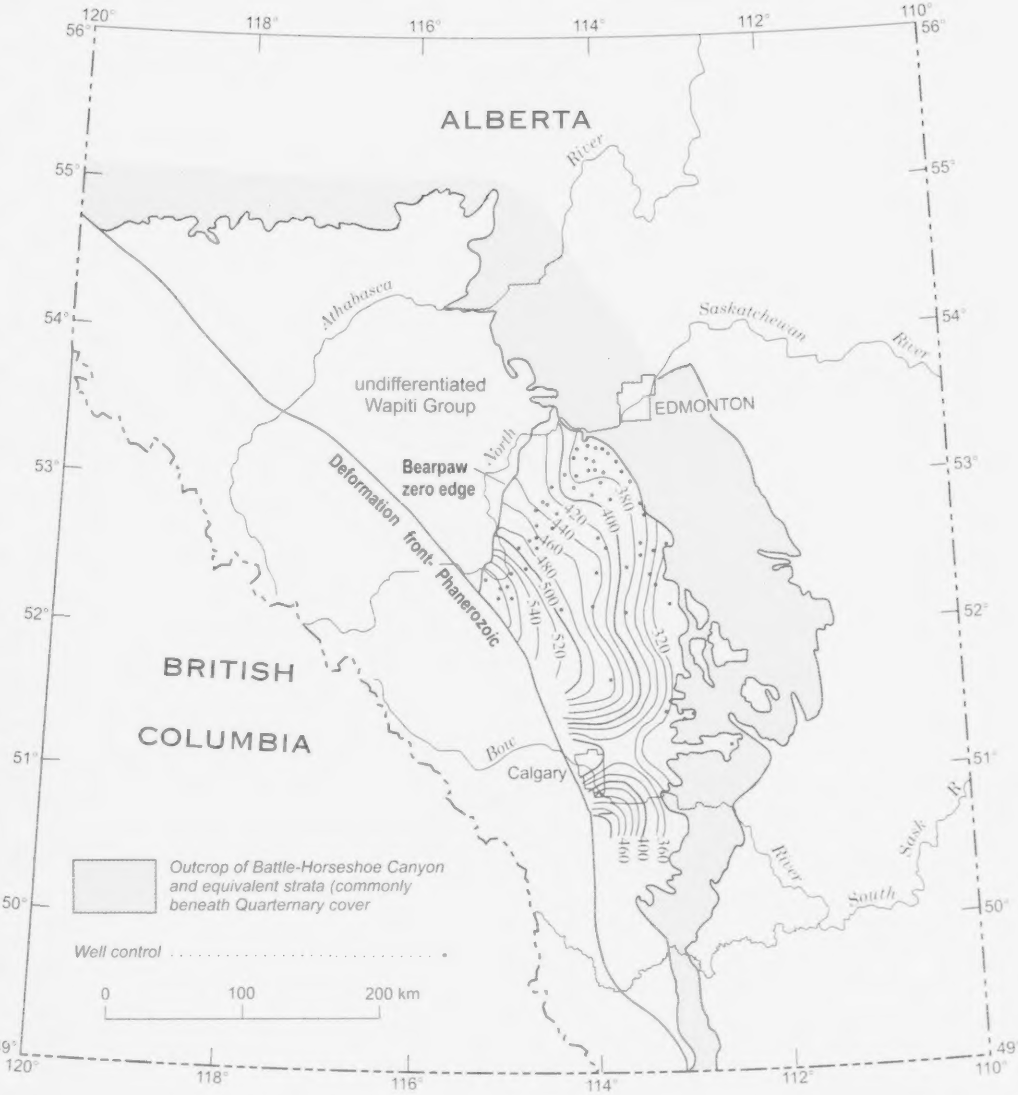


Figure 6. *Isopach (metres) of the Horseshoe Canyon Formation, southern Alberta (from Dawson et al., 1994).*

Drumheller marine tongue (about two thirds of the thickness from the base) and including coal seams #0 to #10; 2) Middle Edmonton, from the top of the Drumheller marine tongue (DMT) to the top of the Battle Formation, including coal seams #11 and #12; and 3) Upper Edmonton (member E of some authors), from the Battle to the base of the Paskapoo Formation, later formally named the Scollard Formation by Gibson (1977) who included it in the Edmonton Group. In this study, it is treated as part of a separate succession. Ower (1960) proposed a slightly different subdivision consisting of 1) Member A of sandstone, shale and coal seams #0 to #7; 2) Member B of green shale and sandstone and the Drumheller marine tongue in the middle but nearly barren of coal except for the minor seams #8 to #10; 3) Member C of grey shale, sandstone and thick coal seams #11 and #12; 4) Member D of the Kneehills Tuff Zone (Whitemud and Battle formations); and 5) Member E of grey shale, fine- to coarse-grained sandstone and thick coal seams (Scollard Formation).

Elliot (1960) returned to the subdivisions of Allan and Sanderson (1945) but acknowledged that the Drumheller marine tongue pinches out northwest of Drumheller and is therefore difficult to use as a regional marker. He suggested that the Kneehills Tuff Zone (KTZ) is the only persistent regional correlation unit. This sentiment was echoed by Campbell (1962) and Srivastava (1968) who both

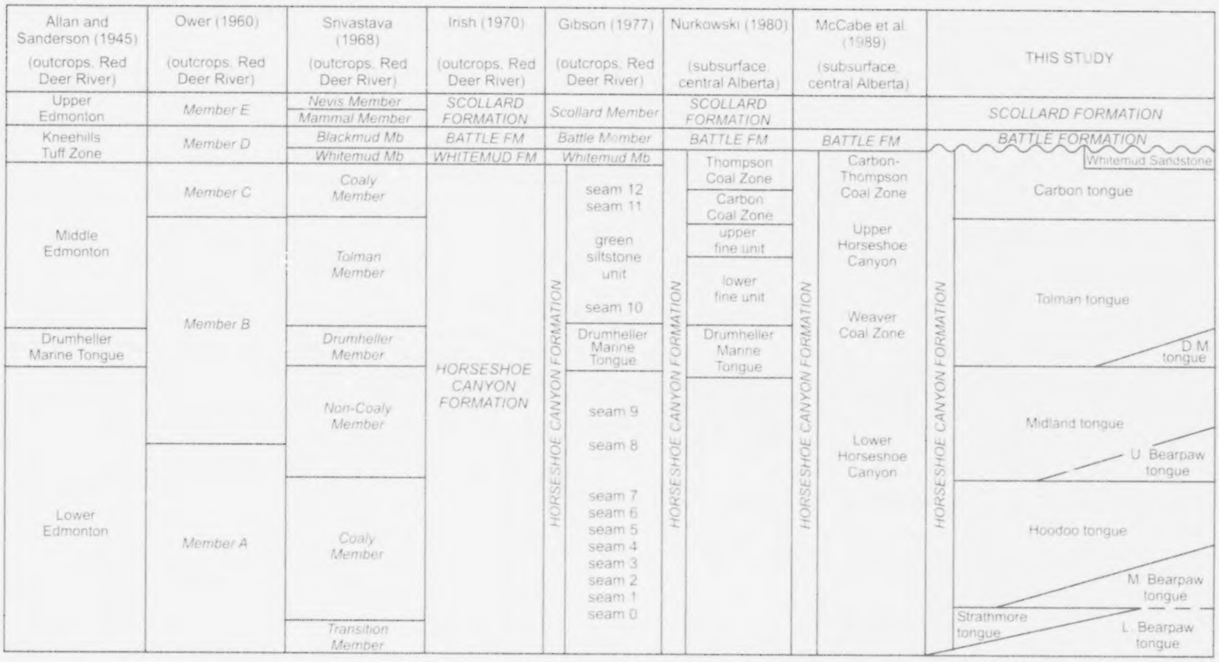


Figure 7. *Historical attempts at internal subdivision of the Horseshoe Canyon Formation, central Alberta, primarily utilizing outcrops in the Red Deer River valley near Drumheller (modified from Hamblin, 1998b).*

mentioned that the KTZ included the only floral and faunal break in the sequence. A macrofloral and dinosaur faunal break at the Battle Formation was confirmed by Srivastava (1968, 1970) (Fig. 3) who also suggested that there was a floral distinction between those sediments below and above the Drumheller marine tongue (DMT). Ritchie (1960) gave radiometric dates for the Kneehills Tuff generally in the 66–67 Ma range, and Irish and Havard (1968) and Irish (1970) indicated that the Whitemud-Battle-Kneehills Tuff sequence was consistently present at the top of the Edmonton Group and represents a fundamental chronostratigraphic marker of regional extent.

Irish (1970) (Fig. 7, 8) stated that Ower's subdivisions were based on outcrop and useful only locally, and suggested new type or reference sections for the three formations he defined in the Edmonton Group. The Horseshoe Canyon Formation includes all strata between the Bearpaw and the distinctive Whitemud sandstone, and so is equivalent to the Lower and Middle Edmonton of Allan and Sanderson (1945) and Members A, B and C of Ower (1960) (Irish, 1970). The Formation has a gradational base placed at the base of the lowest thick sandstone above the Bearpaw, a sharp to gradational conformable top with the Whitemud, and the Drumheller marine tongue is locally present about two-thirds up from the base (Stelck et al., 1976; Glass, 1990). The type section (Fig. 4) designated was the entire Red Deer River Valley between East Coulee to the southeast (Twp. 28, Rge. 18W4) and Big Valley Creek to the north (Twp. 34, Rge. 21W4), although the name "Horseshoe Canyon" comes from a nearby exposure area where only the upper portion of the strata are exposed.

Nurkowski and Rahmani (1984) (Fig. 7), studying the upper Horseshoe Canyon Formation, described a lower fine-grained unit immediately overlying the Drumheller marine tongue, with bentonite time lines and no coal (equivalent to the lower Middle Edmonton subdivision of Allan and Sanderson, 1945, the upper Member B of Ower, 1960, and the informally defined Tolman member of Srivastava, 1968). They also described an upper coal-bearing unit (Carbon-Thompson Coal Zone) immediately below the Whitemud Formation and Kneehills Tuff time line (equivalent to the upper Middle Edmonton Group of Allan and Sanderson, 1945, to the Member C of Ower, 1960, and to the Eastend of Cypress Hills).

The Whitemud Formation, consisting of white sandstone, conformably and gradationally overlies the Horseshoe Canyon and Eastend formations, and has a sharp, unconformable top with the Battle Formation, although it may be erosionally overlain by Frenchman-Paskapoo sandstone (Irish, 1970; Lerbekmo, 1985; Lerbekmo and Coulter, 1985b). The Battle Formation, comprising dark shale, has a sharp unconformable base and an upper contact that appears conformable with the Scollard and Willow

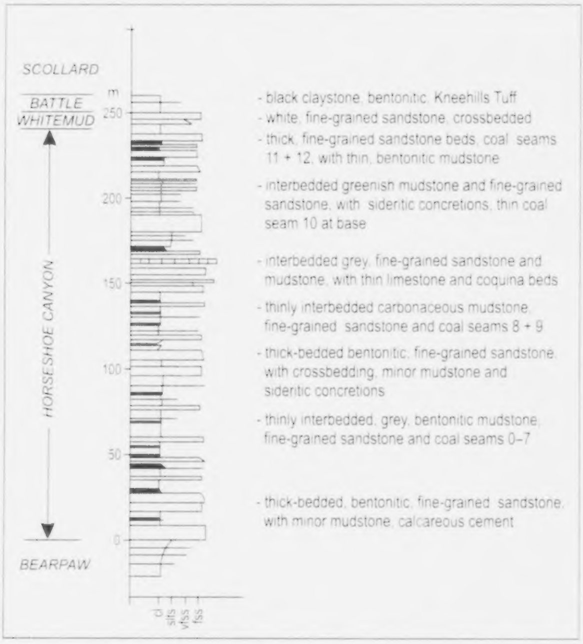

SCOLLARD
BATTLE
WHITEMUD
HORSESHOE CANYON
BEARPAW
m
250
200
150
100
50
0
cl
slts
vfss
fss
- black claystone, bentonitic, Kneehills Tuff
- white, fine-grained sandstone, crossbedded
- thick, fine-grained sandstone beds, coal seams 11 + 12, with thin, bentonitic mudstone
- interbedded greenish mudstone and fine-grained sandstone, with sideritic concretions, thin coal seam 10 at base
- interbedded grey, fine-grained sandstone and mudstone, with thin limestone and coquina beds
- thinly interbedded carbonaceous mudstone, fine-grained sandstone and coal seams 8 + 9
- thick-bedded bentonitic, fine-grained sandstone, with crossbedding, minor mudstone and sideritic concretions
- thinly interbedded, grey, bentonitic mudstone, fine-grained sandstone and coal seams 0–7
- thick-bedded, bentonitic, fine-grained sandstone, with minor mudstone, calcareous cement

Figure 8. *Horseshoe Canyon composite type section, Red Deer River valley between Twp. 28, Rge. 18W4 and Twp. 34, Rge 21W4 (adapted from Irish, 1970, and taken from Hamblin, 1998b).*

Creek formations in southern Alberta, but is conformable to disconformable beneath pre-Frenchman-Paskapoo erosion in the southeast (Irish, 1970; Lerbekmo, 1985; Lerbekmo and Coulter, 1985b). Conformably within the Battle in all areas, commonly in the upper half, are one to several thin tuff beds, the "Kneehills Tuff" or "KTZ" (Allan and Sanderson, 1945; Irish and Havard, 1968; Lerbekmo, 1985).

Present work (minor revision)

The Horseshoe Canyon Formation (Irish, 1970) generally represents the sand-dominated molassic clastic wedge of late Campanian–Maastrichtian age, which overlies and intertongues with the marine Bearpaw Formation in central and southern Alberta. It comprises varicoloured, thinly interbedded fine-grained sandstone, siltstone, mudstone, and coal, and is well-exposed in the valley of the Red Deer River in the vicinity of the City of Drumheller. It is up to 550 m thick in the study area, and present in the subsurface throughout west-central Alberta.

It is now apparent, as detailed below (Lerbekmo and Coulter, 1985b; Catuneanu and Sweet, 1999; Lerbekmo and Braman, 2002), that the Battle Formation is separated from the Horseshoe Canyon (and Whitemud sandstone) by a significant regional unconformity. Therefore, the top of the Horseshoe Canyon Formation should be revised to be placed at the disconformable top of the Whitemud sandstone, and the white, pedogenically altered sandstone horizon should now be included within the formal definition of the formation. The Battle Formation should be regarded as more closely allied to the overlying Scollard succession.

The present revision requires downgrading of the former Whitemud Formation to an informal (but commonly recognized in outcrop) pedogenically altered horizon at the top of the uppermost unit of the Horseshoe Canyon Formation, present in some form at many (but not all) locations. In this report, it is considered to represent a well-developed paleosol beneath the sub-Battle unconformity. It is therefore included within the Carbon tongue of the Horseshoe Canyon Formation as a regionally distributed, pedogenically altered diagenetic horizon, rather than as a separate formation. It represents a prominent zone of alteration associated with the regional unconformity beneath the Battle-Scollard sequence, which marks the top of the third-order Dinosaur Park-Bearpaw-Horseshoe Canyon Sequence.

Horseshoe Canyon Formation (formal revision of upper boundary)

Definition, type and reference sections

The Horseshoe Canyon Formation, named by Irish (1970), comprises varicoloured, thinly interbedded fine-grained sandstone, siltstone, shale and coal. Characteristic are great variability in lithology and bedding, lensing and interfingering of bedding, numerous thin coal seams and zones, abundant bentonitic content rendering a typical "popcorn" weathering style, hoodoo- and badland-type weathering profiles, iron-rich calcareous concretions, abundant dinosaur bones and petrified wood, and some oyster shell coquinas. It is herein suggested that the top boundary of this unit be revised to include the strata assigned to the previous Whitemud Formation, which can be interpreted as a sub-unconformity paleosol alteration horizon rather than a separate formation-rank unit.

The Horseshoe Canyon Formation is spectacularly exposed along the Red Deer River valley and I propose to retain the original composite type section designated by Irish (1970) as the continuous exposures between Twp. 28, Rge. 18W4 in the vicinity of the village of East Coulee to Twp. 34, Rge. 21W4 in the vicinity of Dry Island Provincial Park. This section provides complete coverage of the unit from the basal transition with the underlying Bearpaw Formation to the sharp upper contact with the overlying Battle Formation. A subsurface reference section is here designated as the cored interval from C.P.O.G. Strathmore

7-12-25-25W4 from 598–1640 feet (182–500 m) (Hamblin, 1998). This section provides continuous core for all but the uppermost 76 m of the unit and geophysical logs for the entire formation. The lithology is dominated by thinly interbedded sandstone, siltstone and numerous coal seams, producing typical geophysical log signatures with highly serrated gamma ray and porosity traces. This is true, except in lower zones, where significant marine shale tongues are present at the bases of the East Coulee, Hoodoo, and Midland tongues, and in the Tolman tongue, where coal is virtually absent, the only part of the Horseshoe Canyon where the porosity log traces are relatively smooth.

Lower and upper contacts

The Horseshoe Canyon Formation is recognizable in the surface and subsurface throughout the southwestern Plains of Alberta. It overlies, and intertongues with, the Bearpaw Formation with a conformable gradational contact. For consistency and ease of demarcation, that contact is placed at the base of the lowest thick sandstone body that is associated with coal, above the chocolate-brown mudstone of the Bearpaw Formation (Irish, 1970). As discussed below, the diachronous and intertonguing relationship between the Bearpaw and Horseshoe Canyon formations allows this contact to be placed at several different points in the stratigraphy, depending on geographic location.

Irish (1970) placed the top of the Horseshoe Canyon Formation at the base of the white sandstone of his "Whitemud Formation". However, the magnetostratigraphic studies of Lerbekmo and Coulter (1985a, b), and the sedimentological, stratigraphic, and palynological studies of Cateneanu and Sweet (1999) have now confirmed the existence of an early Late Maastrichtian hiatus of significant duration between the Whitemud sandstone and the Battle Formation in Alberta and southwest Saskatchewan (see below). The top of the Whitemud is an isochronous time line (Lerbekmo and Coulter,1985b). In addition, Gibson (1977) and Lerbekmo and Coulter (1985b) stated that the upper contact of the Battle with the Scollard is conformable, although Russell (1983) had suggested an unconformity there. It is now clear that the Horseshoe Canyon Formation is disconformably overlain by dark grey bentonitic mudstone of the Battle Formation and/or grey, buff, or brownish medium- to coarse-grained sandstone or bright yellowish-greenish shales of the Scollard Formation. This supports the need for some nomenclatural revision at this contact.

Thickness and regional extent

The formation is traceable in the surface and subsurface in an arcuate band throughout most of western Alberta between Twp. 15–75, and west of Rge. 10W4. The unit is approximately 250 to 300 m thick in the type area, and thickens to the north and west to about 500 m within the present study area. It pinches out depositionally to the east and southeast and ultimately thins to an erosional edge in central Alberta. In the Plains, the Horseshoe Canyon Formation is generally about 250 to 300 m thick along Red Deer River valley, thickening rapidly to the west, thinning to the east (Allan and Sanderson, 1945; Ower, 1960; Gibson, 1977; Srivastava, 1970) and to the south to 122 m on Little Bow River (Williams and Dyer, 1930). The Whitemud sandstone, at the top of the formation, is up to 23 m thick in Cypress Hills where pre-Frenchman Formation erosion may cut it out completely, but it is generally 4 to 8 m thick over most of central Alberta (Furnival, 1950; Gibson, 1977). Generally, the Horseshoe Canyon Formation totals about 227 to 275 m, averaging 250 m (Irish, 1970; Stelck et al., 1976; Gibson, 1977).

In the southern Foothills, the thickness of the partly correlative St. Mary River Formation (which extends north to about Twp. 14) has been variously given as 487 m on Oldman River and 914 m to the west (Williams and Dyer, 1930); up to 950 m (Rahmani and Schmidt, 1975), and 240 m on Oldman River thickening westward to 450 m (Young and Reinson, 1975); 460 to 480 m (Yurko, 1976), and 354 m on St. Mary River (Glass, 1990); and 457 m on Oldman River, and 762 m on Crowsnest River (Glass, 1990). Furnival (1950) expressed doubt about the excessive 460 to 490 m thicknesses because of thrusting in the Monarch Fault Zone, but Hamblin (1998d) measured 533 m for the complete St. Mary River Formation on Oldman River near Monarch.

In the Cypress Hills, the Eastend Formation, approximately equivalent to the Horseshoe Canyon Formation, is 36 m thick in southeastern Alberta, 19 m thick at Ravenscrag Butte and 21 m thick at Eastend (Furnival, 1950; Glass, 1990). The overlying Battle Formation ranges from 3 to 14 m in thickness, averaging 6 m, but also may be partly to completely eroded by pre-Scollard and Frenchman formation downcutting (Gibson, 1977; Glass, 1990). The Kneehills Tuff within the Battle Formation may exist as one bed 2.5 to 30 cm thick, or several thin beds within a 3.5 m interval (Kneehills Tuff Zone, "KTZ") and probably is not continuous throughout its vast area of occurrence (Ritchie, 1960; Lerbekmo, 1985).

Description

Sandstone: pale grey, well sorted, very fine- to coarse-grained (primarily fine- to medium-grained); in lens-like multistoried, scour-based, fining-upward channel or splay units up to 10 m thick; trough-crossbedding, ripple crosslamination, low-angle lamination, inclined bedding and inclined heterolithic stratification accoaunts for about 30% of strata.

Siltstone: generally greenish grey, sandy or muddy; fining-upward units up to 15 m thick; typically pedogenically homogenized (massive, blocky, rubbly textures with common vertic features) with thin sandy horizons, sideritic concretion horizons and calcrete beds; about 60% of strata.

Mudstone: brownish to greyish, silty, laminated; may be burrowed, may contain oyster shells; mostly uncommon.

Coal: black, lignitic to bituminous, thin to thick coal and carbonaceous mudstone seams; commonly sharp rooted bases and sharp tops, up to 3 m thick; about 10% of strata.

Sideritic concretion horizons: ubiquitous, range from thin horizons of scattered sideritic concretions to laterally continuous sandy limestone beds up to 1 m thick with gradational bases and sharp irregular tops, roots, wood fragments, slickensides.

Whitemud sub-unconformity pedogenic horizon: distinctive white quartz and kaolinite-rich sandstone bodies, commonly present at the top of Horseshoe Canyon beneath the sub-Battle unconformity, representing leached albic eluvial horizon ("ganister") of a regionally extensive spodosol at the maximum regression surface for the Horseshoe Canyon delta plain succession.

Magnetostratigraphic data

Lerbekmo and Coulter (1985a) were able to correlate the magnetostratigraphic zonation from the Red Deer River valley with confidence to the foram-based polarity standard from Gubbio, Italy. They found that Horseshoe Canyon strata encompass polarity chrons 33/32r/32/31r/31/30r, and the Campanian–Maastrichtian boundary should be placed within the lower half of the Horseshoe Canyon at about the level of Coal Zone #5. Magnetostratigraphic studies of upper Horseshoe Canyon and Scollard Formation strata in the Red Deer River valley by Lerbekmo and Coulter (1985a,b) confirmed that the Whitemud-Battle contact closely coincides with polarity boundary 30r–30n (i.e. upper Horseshoe Canyon and Whitemud = 30r, Battle and lower Scollard = 30n). This contact appears to represent a significant surface across southern Alberta, possibly a hiatus. Additionally, there is no magnetostratigraphic or sedimentological evidence to suggest a regional stratigraphic break at the Battle–Scollard contact (Lerbekmo and Coulter, 1985b).

Further, very important work by Lerbekmo and Braman (2002), involving an integrated magnetostratigraphic-biostratigraphic correlation of the Bearpaw-Horseshoe Canyon-Eastend succession in Red Deer valley and that in Cypress Hills, provided a very detailed chronostratigraphic framework that crosses the eroded area between these two sites. This work determined that the base of the Bearpaw Formation is within magnetochron 33n, and that the Battle Formation (overlying the Horseshoe Canyon) is within magnetochron 30n in both areas, essentially establishing near-isochronous boundaries at the base and top of the Bearpaw-Horseshoe Canyon regressive succession, at least within the southern Alberta region. However, between these two boundaries, the Bearpaw-Horseshoe Canyon contact is clearly diachronous, younging to the southeast, occurring in 32r at Red Deer River (late Campanian), and in 31n in Cypress Hills (Early Maastrichtian). The Campanian–Maastrichtian boundary occurs at the top of magnetochron subzone 32n.1n near the level of the Drumheller marine tongue in Red Deer River valley. These data allow the detailed correlation of various parts of the third-order sequence for the first time.

Through detailed magnetostratigraphic work, Lerbekmo (1985) showed that uneroded Battle Formation was deposited during polarity chron 30r whereas the overlying lowest Frenchman Formation was deposited during polarity chron 30, and the up to 70 m of erosional relief on the unconformity separating the two may represent only 300,000 years of time. In addition, the sub-Frenchman Formation disconformity in Cypress Hills is represented by 50–60 m of Horseshoe Canyon-Scollard strata in central Alberta, and the Battle Formation is 0.5 Ma younger in central Alberta than in Cypress Hills (i.e., while the Battle was being deposited in Red Deer River valley, it was being eroded in Cypress Hills, Lerbekmo, 1985).

Age and correlation

The Horseshoe Canyon Formation of the Plains is underlain by, and intertongues with, the late Campanian–Maastrichtian Bearpaw Formation (Caldwell, 1968; Kurita and McIntyre, 1995). The Dorothy Bentonite, in the upper Bearpaw Formation in the southeast part of my study area, has yielded a Rb/Sr date on biotite of 73.2 Ma (Baadsgaard and Lerbekmo, unpublished data, quoted by Lerbekmo and Braman, 2002). The Campanian–Maastrichtian boundary was formerly placed near the base of the Bearpaw (Srivastava, 1968), or near the top of the Bearpaw (Kurita and McIntyre, 1995). However, the Campanian–Maastrichtian boundary is now placed near the level of Coal Zone #10 and the Drumheller marine tongue (Lerbekmo and Braman, 2002) and the top of the Bearpaw is younger to the southeast (Russell and Landes, 1940; this study). The Horseshoe Canyon flora and fauna is Campanian–Maastrichtian in age, and the overlying Kneehills Tuff can be radiometrically dated to the late Maastrichtian and is overlain by the late Maastrichtian to early Paleocene Battle and Scollard formations (Braman et al., 1995). The Horseshoe Canyon has a conformable base and disconformable top, is approximately equivalent to the upper Brazeau Formation of western Alberta, the upper Wapiti Formation of northern Alberta, the St. Mary River Formation of southwestern Alberta and the Eastend-Whitemud Formation of southern Saskatchewan (Williams and Dyer, 1930; Rahmani and Lerbekmo, 1975; Jerzykiewicz and McLean, 1980). Near the top of the unit, the former Whitemud Formation, here identified as a regionally distributed, sub-unconformity pedogenically altered zone, has been correlated to the Colgate Member of the Fox Hills Formation in northern U.S., based on similarity of lithology and petrography, and to the upper St. Mary River Formation, by stratigraphic position (Russell and Landes, 1940; Furnival, 1950; Glass, 1990).

The Kneehills Tuff, within the overlying Battle Formation, is correlated to other tuff horizons identified at the top of the St. Mary River (Glass, 1990), upper Brazeau (Elliot, 1960), and Battle formations (Furnival, 1950), and occurs throughout the Twp. 1–67 area in outcrop (Irish and Havard, 1968). These ashfall beds have been variously dated at 75 Ma (Pb/Pb), 66–68 Ma (K/Ar on sanidine), 65 Ma (biotite from bentonite immediately above)(Ritchie, 1960), 66 Ma K/Ar (Dodson, 1971), 64–65 Ma (Williams and Burk, 1964), 66–67 Ma (K/Ar, Stelck et al., 1976), 66 Ma (K/Ar dating by Folinsbee et al., 1961, as quoted by Srivastava, 1968), and a magnetostratigraphic date of 66.5–67 Ma (Lerbekmo and Coulter, 1985a, b). These dates centre about the range 66–67 Ma, an approximate date for the end of Horseshoe Canyon Formation deposition.

Clearly the Horseshoe Canyon Formation is late Campanian to mid-late Maastrichtian in age, spanning a time interval of about 7 Ma, and deposited shortly before the Cretaceous–Tertiary boundary.

Environment of deposition and paleoflow

Sediments of the Horseshoe Canyon Formation were deposited in a variety of fluvial, floodplain and paralic depositional settings on a broad coastal plain along the western margin of the Western Interior Seaway. Environments of deposition include meandering rivers, estuarine channels, shorefaces, laterally extensive floodplains, swamps and paleosols. Sediment dispersal was toward the east-southeast and shorelines were oriented north-northwest–south-southwest.

Coal zones

In the valley of the North Saskatchewan River near Edmonton, the coal seams were first described by Tyrrell (1887), and studied in detail by Dowling (1910), Beach (1934) and Pearson (1961). Here there are up to 10 poorly exposed seams generally less than 2 m thick, of which four were mined extensively in the first half of the twentieth century (Pearson, 1961). The Clover Bar Coal Zone (or #4 seam) was the most intensively studied, and actually comprises several less continuous seams 1–2 m thick, separated by thin shale beds (Pearson, 1961).

In the Red Deer River valley, coal seams were first described by Tyrrell (1887), and first studied in detail by Allan (1921) and Allan and Sanderson (1945) (Fig. 7). Most coal extracted in early years was used to fuel steam locomotives and for local needs (McCabe et al., 1989). The coals are concentrated into ten commercial "zones" between the base of the Horseshoe Canyon and the Drumheller marine tongue (DMT) (many coals in Member A, few in Member B), and two persistent horizons above the DMT (near the top of Member C) (Ower, 1960; Stelck et al., 1976). The seams are thickest near the outcrop belt and thin rapidly to zero as the rank increases to the west (Yurko, 1976). There is rapid thinning and thickening of individual seams over short distances, making seam correlation difficult, although "coal zones" tend to be somewhat more extensive and continuous (Allan and Sanderson, 1945; Yurko, 1976; McCabe et al., 1989). Lerbekmo and Coulter (1985b), employing very detailed magnetostratigraphic sampling, found that at least some of the section-to-section correlations of Seams 11 and 12 in Red Deer River valley, as published in older literature, cannot be justified. This has resulted in mislabelling of seams, and general overemphasis of the concept of significant regional correlation of these numbered coal zones (Lerbekmo and Coulter, 1985b). The coals result from organic accumulations in shore-parallel peat-forming mires, and therefore should be more continuous in northeast-southwest trends (McCabe et al., 1989).

The lower Horseshoe Canyon Formation is most important for coal, with continuous seams with thin clastic partings ("Drumheller Coal Zone" of McCabe et al., 1986), which represent widespread peat accumulation due to in situ growth during times of low sediment accumulation (Allan and Sanderson, 1945). The best coals are associated with the many tongues of marine influence that characterize the lower transitional 50 m of the formation, hence the extent of marine strata of the Bearpaw Formation and DMT are conceptually important (McCabe et al., 1986; Beaton et al., 2002). This study also illustrates transgressive marine tongues of greater regional extent and their relation to coal concentration. These coals were deposited in shoreline-parallel peat swamps 30 to 50 km back from the actual shoreline (McCabe et al., 1989). Repeated transgressive-regressive phases resulted in extensive stacked coal seams with thicknesses over 2 m (McCabe et al., 1989). These are organized into north-south trends, especially well-developed west of the outcrop belt (McCabe et al., 1989). According to Gibson (1977), the coals are associated with three types of sandstone deposits: 1) coarsening-upward bayfills, 2) thick northeast-trending channels, and 3) thin, fining-upward crevasse splays.

Coals in the upper Horseshoe Canyon are encased in predominantly sandy fluvial sediments and are less continuous, except in locations far from major channels (McCabe et al., 1986). Nurkowski (1980) and Nurkowski and Rahmani (1984) studied the coal-bearing unit 60-80 m thick at the top of the Horseshoe Canyon Formation in central Alberta and described a general coarsening-upward, more fluvial-upward, succession deposited on a broad, low-lying coastal plain west and north of the retreating Bearpaw sea. This unit is under- and overlain by bentonitic markers interpreted to be synchronous time lines. The Carbon Coal Zone contains thick channel sandstone, overbank laminated mudstone and coal seams up to 4 m thick, distributed in northwest-southeast trends beside and parallel to channel trends, and only correlatable along these trends. The overlying Thompson Coal Zone has coarser sandstone channels, mudstone and seams that, likewise, parallel the northwest-southeast channels in sinuous bands.

In outcrops of the Red Deer River valley, Horseshoe Canyon coals are thought to be distributed vertically in specific stratigraphic intervals. Although individual seams are not laterally continuous over great distances (as implied by earlier literature), some coal-prone intervals have been identified as follows: 1) seams #0 and #1 in the basal transition zone, and seams #2 to #7 in the lower coaly unit (Member A of Ower, 1960; Drumheller Coal Zone of McCabe et al., 1989); 2) a less coaly unit overlain by seams #8 to #10 just beneath the DMT, and then overlain by the noncoaly green mudstone unit (all part of Member B of Ower, 1960); and 3) seams #11 and #12 in the upper coaly unit (Member C of Ower, 1960) (Yurko, 1975). These intervals are important for stratigraphic and sedimentological analysis and the following is summarized from individual outcrop descriptions in the Red Deer River valley by Allan and Sanderson (1945) and Gibson (1977) (see also Fig. 7, 8). Although these authors list these intervals as coal "seams" they, in fact, represent coal "zones" with some lateral continuity, each including several individual overlapping seams that are less laterally continuous. In ascending order these Coal Seams ("Zones") are:

Seam #0: lowest, thin, thins to east, clean and vitreous, 0.2–0.8 m thick, 12–16 m above Horseshoe Canyon Formation base (as exposed in outcrop at Willow Creek).

Seam #1 (Drumheller Seam): carbonaceous shale and coal, vitreous with thin bentonite bed, 0.9–1.4–3.3 m thick, 18–27 m above base, thins to east, cut out by channel erosion in places, lowest mineable seam, commonly overlain by marine shale tongue, abundant silicified tree stumps at Willow Creek.

Seam #2, 0.2–1.8 m, thickens to southeast, 11–18 m above #1, 28–45 m above base, vitreous with lenses of carbonaceous shale, present southeast of Drumheller, was main seam at Atlas Mine Historical Site.

Seam #3: thin, 0.2–1.5 m, 30–52 m above base and 2.5–4.0 m above #2, mostly carbonaceous shale.

Seam #4: thin, 0.2–0.5 m, 3–5 m above #3, eroded by channels in some places, vitreous to dull, good marker.

Seam #5 (Newcastle Seam): 0.3–2.0 m thick, 4–7 m above #4, vitreous with carbonaceous shale interbeds, exposed at Drumheller townsite level, entire stratigraphic interval from #1 to #5 thickens to southeast (Lerbekmo and Coulter, 1985a, placed the Campanian–Maastrichtian boundary at this level).

Seam #6: thin, 0.2–1.0 m, thickens to southeast, 14–22 m above #5, mostly carbonaceous shale with woody layer, good marker.

Seam #7 (Daly Seam): 0.8–3.3 m thick, very variable but thickens to north, 6–8 m above #6 and 85 m above Horseshoe Canyon base, vitreous with carbonaceous shale lenses, generally present northwest of Drumheller.

Seam #8: 0.1–2.0 m splitting into two seams, 35–40 m above #7, mostly carbonaceous shale with bentonite bed, distinctive marker.

Seam #9: thin, 0.1–0.7 m, 13–20 m above #8, vitreous with bentonite bed, eroded by sandstone channel in places, exposed at Bleriot Ferry.

Seam #10 (Marker Seam): thin, 0–1 m thick, brownish carbonaceous shale in greenish siltstone, 37–41 m above #9, approximately 180 m above Horseshoe Canyon Formation base, passes to siltstone to the north, approximately at or immediately below DMT, exposed at top of Horsethief Canyon (Lerbekmo and Braman, 2002, placed the Campanian–Maastrichtian boundary at this level).

Seam #11 (Carbon Seam): 0.2–1.6 m thick, 53–62 m above #10, about 225 m above Horseshoe Canyon Formation base, vitreous to dull with abundant carbonaceous shale, wood fragments and bentonite beds, extensively mined, exposed at Horseshoe Canyon and north of Morrin Bridge.

Seam #12 (Thompson Seam): 0.1–1.5 m thick, 7–16 m above #11 and immediately beneath the Whitemud Formation, vitreous with some carbonaceous shale, commercially mined, exposed at Horseshoe Canyon and north of Morrin Bridge.

Paleoclimate

Deposition of the Horseshoe Canyon-St. Mary River-Eastend nonmarine wedge occurred at a paleolatitude of about 60° N, although the late Maastrichtian climate was warmer than the present-day climate at that latitude (Richardson et al., 1988). Allan and Sanderson (1945), Furnival (1950), and Nurkowski and Rahmani (1984) all suggested a generally warm humid to temperate climate, similar to the current Gulf of Mexico, as evidenced by the abundance of coal, fossils of sequoia trees, dinosaur bones and the lack of evidence of desiccation. The Bearpaw sea, at maximum extent, occupied the southern half and northeastern quarter of Alberta and likely had a moderating effect on the climate.

Srivastava (1970) provided the most detailed palynological and paleoclimatic study of the evolution of the Edmonton Group in central Alberta. He interpreted the climate during deposition of the lower Edmonton Group (up to the DMT) as being generally subtropical and humid, with rainforest vegetation, and during deposition of the middle Edmonton Group (from the base of the DMT to the base of the Battle) as subtropical to temperate, becoming more temperate through time. The Battle Formation was interpreted as representing a cooler climate with savannah vegetation; from the base of the Battle to the Cretaceous–Tertiary boundary, the palynological evidence suggests a warm temperate climate. This upward increase in aridity was also noted in the St. Mary River Formation of southwestern Alberta by Nadon (1988), based on the upward-increasing occurrence of paleosol horizons. In the Red Deer River valley, there is some evidence for an upward increase in aridity to a point above the DMT, followed by a return to more humid conditions (D. Eberth, pers. comm., 2002; see below in this study).

In the St. Mary River Formation of the southern Foothills, Jerzykiewicz and Sweet (1988) recorded a predominance of intermediate climatic indicators that pass upward into more arid climatic conditions of the overlying lower Willow Creek Formation. In the upper Brazeau Formation of the central Foothills the same authors found evidence of intermediate climatic conditions passing upward into a more humid, coal-bearing sequence and then back into the intermediate climatic facies of the overlying lower Coalspur Formation. The geographical difference in climatic conditions was related to a difference in geographic distribution of topographic and orographic influence, whereas the vertical changes in climatic indicators within this wedge may relate to proximity to marine tongues and transgressions (Jerzykiewicz and Sweet, 1988).

The Whitemud sandstone and Battle Formation may represent unusual climatic or topographic conditions wherein rapid mechanical weathering and intense chemical diagenesis produced in situ kaolinitization of the feldspar grains in the Whitemud, with a rise in water table, widespread development of shallow lakes and slow deposition during the time of Battle Formation deposition (Lerbekmo, 1985). As previously stated, there is likely a regional unconformity between the Whitemud and Battle units, which separates the underlying Bearpaw-Horseshoe Canyon third-order sequence from the overlying Battle-Scollard third-order sequence. Sweet and Braman (1992) cited evidence for a continent-wide increase in wetness during the time of Scollard Formation deposition, following Horseshoe Canyon Formation deposition, and immediately prior to the Cretaceous–Tertiary boundary.

Paleontology

The Bearpaw Formation is famous for the well-preserved occurrences of the ammonite *Placenticeras* within concretions and the semiprecious gem-quality "Ammolite" which makes these valuable (Braman et al., 1995; Mychaluk, 2002). In addition, a well-preserved diverse assemblage of arthropods, bivalves, gastropods, vertebrates and palynomorphs is present (Braman et al., 1995).

The paleontology of the Horseshoe Canyon-St. Mary River-Eastend clastic wedge is varied and has received little detailed study in recent years. In central Alberta, macrofossils are abundant only at certain horizons in certain facies and are different from those of the underlying Belly River and Judith River formations, but similar to those of the overlying Scollard Formation (Williams and Dyer, 1930). Most consist of freshwater and terrestrial gastropods and pelecypods, brackish water oyster, clam, and gastropod beds, with minor wood fragments, fish and turtles (Williams and Dyer, 1930; Allan and Sanderson, 1945; Stelck et al., 1976). Plants include ginkgoes, poplars, pines, sequoias, and cycads with a decided Lancian affinity, and upright tree trunks occur above some coal seams (Williams and Dyer, 1930; Allan and Sanderson, 1945; Stelck et al., 1976). The most important break in the pollen and dinosaur records occurs within the KTZ (Kneehill Tuff Zone), suggesting a continuous depositional record through most of the Horseshoe Canyon (Sternberg, 1947; Elliot, 1960; Srivastava, 1970). The presence of abundant megaspores through most of the stratigraphy indicates a continental setting (Wall et al., 1971). A lesser change in the flora occurs at the base of the DMT (Srivastava, 1968, 1970). Thus, Srivastava (1970) defined two major paleontological breaks of significance to his study: at the base of the DMT, and at the base of the Battle Formation.

The DMT carries abundant marine to brackish water *Ostrea* and *Corbicula* beds, gastropods, bryozoans and a planktonic microfauna, but no fully marine ammonites as are common in the underlying Bearpaw Formation

(Williams and Dyer, 1930; Allan and Sanderson, 1945; Stelck et al., 1976; Gibson, 1977; Haglund, 2000, 2001). The sandstone above and below the DMT contain some mammal bones and a diverse and characteristic dinosaur fauna dominated by Ornithischia, but with few Saurischia (Williams and Dyer, 1930; Allan and Sanderson, 1945; Stelck et al., 1976). The occurrence of *Leptoceratops* is particularly diagnostic (Williams and Dyer, 1930). During the 1990s, two *Edmontosaurus* bonebeds have been excavated at Bleriot Ferry and at Fox Coulee, containing previously disarticulated elements, a result of scavenging *Albertosaurus* (Lam and Ryan, 2001).

Rahmani (1983, 1988) studied the intertonguing marine Bearpaw and lowest Horseshoe Canyon shoreline sediments in central Alberta and found an abundant ichnofauna including *Ophiomorpha*, *Skolithos*, *Macaronichnus* and others associated with the shallow-marine shoreface, barrier inlet and tidal inlet facies. Oyster shell bars, vertical burrows and *Teridolites* borings occur in the backbarrier facies. Thin shale tongues interbedded with the sandy facies yield marine forams (Wall et al., 1971). The lower fine-grained unit of the upper Horseshoe Canyon Formation yields abundant lacustrine and pond fern megaspores (Nurkowski and Rahmani, 1984).

The Whitemud sandstone, here interpreted as a regionally developed paleosol horizon, has few fossils, consisting only of plant fragments, long tap roots, vertical burrows and casts of vertebrate coprolites and intestines confirming a continental setting (Gibson, 1977; Lerbekmo, 1985). The Battle Formation, likewise, has no diagnostic fossils and the assemblage consists only of megaspores, algae, wood fragments, tap roots, bone and tooth fragments and one questionable *Haplofragmoides* specimen (Furnival, 1950; Irish and Havard, 1968; Binda and Lerbekmo, 1973; Gibson, 1977). This formation is generally considered to be nonmarine. In southeastern Alberta and Saskatchewan the Eastend Formation contains poorly preserved marine and brackish water bivalves in its lower part and a few dinosaur teeth in its upper part (Russell and Landes, 1940; Furnival, 1950).

In the southern Foothills the Blood Reserve Formation forms the prograding shoreline facies overlying the Bearpaw and is characterized by the presence of *Ophiomorpha* burrows (Lerand, 1983), especially near the tops of tidal channel sandstones (Nadon, 1988). A few ammonites and rare *Macaronichnus* burrows are present in the prograding shoreline sandstone (Russell and Landes, 1940; Nadon, 1988), whereas brackish to freshwater pelecypods and gastropods, oyster beds and silicified wood are also present (Jerzykiewicz and Norris, 1994). In the overlying St. Mary River Formation, freshwater gastropods and pelecypods (particularly thick-walled *Unio* shells in fluvial sandstone), terrestrial molluscs, a few aquatic plants and rare dinosaur bones (including the diagnostic *Leptoceratops*) are characteristic (Williams and Dyer, 1930; Russell and Landes, 1940; Jerzykiewicz and Norris, 1992). Brackish water tongues with *Ostrea* and *Corbicula* coquinoid limestone are present near the base (Russell and Landes, 1940; Jerzykiewicz, 1997). Higher in the St. Mary River Formation, thin overbank sandstone beds typically host wood fragments, roots, horizontal and vertical burrows, whereas associated mudstone deposits have wood fragments, nonmarine pelecypods and nonmarine palynology (Rahmani and Schmidt, 1975; Nadon, 1988).

Relation to other units (Fig. 9)

Bearpaw Formation. The Bearpaw Formation in the Cypress Hills area was studied in detail by Lines (1963) who distinguished five members, in ascending order: 1) the Manyberries Member, dark grey shale and siltstone, 200 m thick; 2) the Oxarart Member, medium-grained sandstone, 36 m thick and thinning to the east; 3) the Belanger Member, grey sandy siltstone, 21 m thick; 4) the Thelma Member, fine-grained sandstone, 12 m thick and thinning to the east; and 5) the Medicine Lodge Member, dark grey shale, 23 m thick, overlain conformably and gradationally by the Eastend Formation. In southwestern Alberta, Link and Childerhose (1931), Clark (1931), and Lines (1963) identified thick, dark grey shale with numerous thin bentonite beds and several sandy members (Magrath, Kipp, Ryegrass) overlain by the Blood Reserve Formation (Fox Hills Formation of Sanderson, 1931) sandstone (which Lines, 1963 and Furnival, 1950, equated to the Oxarart Member). All of these studies essentially identified three main coarsening-upward successions in the Bearpaw of southern Alberta and Saskatchewan. It is not clear whether these denote laterally correlative subunits.

In central Alberta the Bearpaw is thicker and shalier to the southeast, and sandier to the northwest, passing eventually into thin glauconitic sandstone with a sparse marine microfauna at its ultimate pinchout in the Edmonton area (Lines, 1963). Lines (1963) divided the formation in east-central Alberta into a lower Young Creek Member, 67 m thick, and a Paintearth Member, 55 m thick, both consisting of dark grey shale with several sandy units. Using an Alberta Research Council deep corehole in the same area, Given and Wall (1971) identified two major sandstone units and three major shale units in the Bearpaw, forming three regressive successions. Habib (1981) identified six coarsening-upward, offlapping regressive cycles in the Bearpaw and basal Horseshoe Canyon Formation in the subsurface of south-central Alberta, in a study area overlapping with that of this report. Cateneanu and Sweet (1999) and Cateneanu et al. (1997; 2000) suggested that the minor shallow-marine sequences of the Bearpaw Formation display reciprocal (out-of-phase)

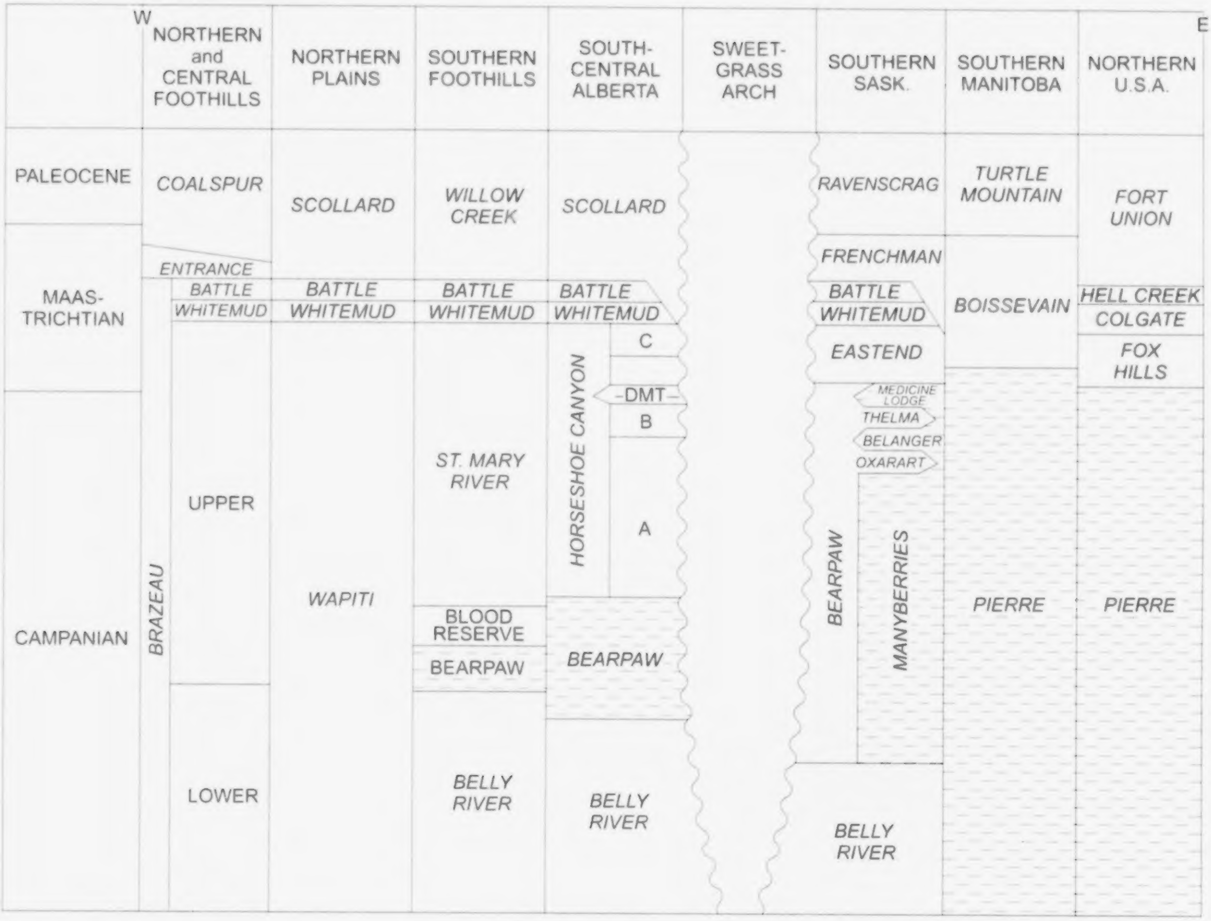


Figure 9. *Generalized stratigraphic correlation chart for Upper Campanian–Maastrichtian strata in the WCSB (from Hamblin, 1998b).*

stratigraphies on opposite sides of the basin, separated by a hinge zone of proximal-to-distal facies change. Migration of the hinge zone (essentially separating the foredeep from the peripheral bulge), and the included coeval transition between transgressive and regressive systems tracts, was interpreted as a response to orogenic cycles of tectonic loading and unloading and flexural behaviour of the foreland lithosphere (Cateneanu et al., 1997; 2000).

Brazeau Formation. In the central Foothills the Bearpaw Formation marine shale pinches out east of the Alberta Syncline axis (Jerzykiewicz, 1997). There, Cyclothems II, III, and IV of the upper Brazeau Formation of the Saunders Group (Jerzykiewicz, 1985) are approximately equivalent to the Horseshoe Canyon-St. Mary River clastic wedge and define an overall coarsening-upward succession. This succession is abruptly overlain by the Entrance Conglomerate at the base of the Coalspur Formation. In the northern Plains the upper Wapiti is approximately equivalent to the Horseshoe Canyon and is capped by a Battle-like unit with a tuff (Irish, 1970).

St. Mary River Formation. In the southern Foothills the Blood Reserve Formation (Fox Hills Formation of the U.S. and of Sanderson, 1931) has sharp but conformable upper and lower boundaries, overlying the Bearpaw marine shale and overlain by the St. Mary River Formation, and is actually a localized shoreline facies of the St. Mary River clastic wedge in southwestern Alberta (Russell and Landes, 1940; Nadon, 1988; Jerzykiewicz, 1997). The overlying St. Mary River Formation, first described by Dawson (1883), encompasses all continental rocks between the Bearpaw and the Willow Creek red beds (Williams and Dyer, 1930). Tozer (1952) identified a white sandstone-mauve shale-tuff bed sequence at the top, directly correlative to the Whitemud-Battle-Kneehills Tuff of central Alberta. The

St. Mary River Formation apparently intertongues northward with the Horseshoe Canyon Formation in the area of Little Bow River (Twp. 14, Rge. 21–22W4), delineating an approximate time-equivalence (Russell and Landes, 1940; Hamblin, 1998a), although no detailed correlation has yet been demonstrated. It is conformably overlain by the Willow Creek Formation on the west side of the Alberta syncline, but a disconformable relationship may occur at that contact on the east side of the syncline (Russell and Landes, 1940).

Cypress Hills stratigraphy. The Cypress Hills are a bedrock-cored plateau on the Plains in southern Alberta and Saskatchewan, separated from the other uplands of southern Alberta by several hundred kilometres of territory where late Campanian–Maastrichtian strata have been eroded. Thus, the relevant strata of Cypress Hills are separated from those of the study area of this report by a 250 km-wide zone of no data. In Cypress Hills, the upper Bearpaw Formation has several sandy members (Thelma, Belanger, Oxarart) separated by marine shale tongues. The Oxarart is correlated to the Blood Reserve of southwestern Alberta whereas the upper 60 m of the Bearpaw Formation is correlated to the lower 60 m of the St. Mary River Formation (Furnival, 1950). The overlying Eastend Formation is equivalent to the upper portion of the St. Mary River (Caldwell, 1968). In Cypress Hills the Eastend Formation sandstone, siltstone and minor coal gradationally overlies the very thick Bearpaw Formation, thickens to the west and passes into Bearpaw marine shale to the east and is gradationally overlain by the Whitemud and Battle formations. It clearly occupies a similar stratigraphic position to that of the Horseshoe Canyon and St. Mary River formations (Russell and Landes, 1940; Furnival, 1950). However, the Eastend Formation is much thinner and, based on the concept that the top of Bearpaw is diachronous but the Battle-Kneehills Tuff represents an approximate time line, the Eastend Formation is likely time-correlative to the upper Horseshoe Canyon of central Alberta (Russell and Landes, 1940) (perhaps to Member C of Ower, 1960), to the upper St. Mary River Formation of southwestern Alberta (Furnival, 1950) and the upper Bearpaw Formation of southwestern Saskatchewan (Russell and Landes, 1940). Lerbekmo and Braman (2002), through integration of detailed magnetostratigraphic and biostratigraphic data, established the definitive correlations between the Bearpaw-Horseshoe Canyon sequence of the Red Deer River and the Bearpaw-Eastend sequence of Cypress Hills. This is discussed in more detail below.

Scollard Formation The Scollard Formation comprises interbedded, brownish, fine- to medium-grained sandstone, siltstone, pale-coloured mudstone and coal of fluvial and alluvial nature (Gibson, 1977). The lower Scollard is characterized by thick sandstone and siltstone with abundant fossils of the latest Cretaceous Lancian Triceratops-Ankylosaurus fauna. The upper Scollard is characterized by thick coals and mudstone. In fact, the Cretaceous–Tertiary boundary is now known to occur at or near the base of the Nevis coal seam within magnetochron 29R (Lerbekmo, 1985; Lerbekmo and Coulter, 1985b; Braman et al., 1995).

INFORMAL LITHOSTRATIGRAPHIC SUBDIVISION

Introduction

As a result of various studies over the last 60 years, we have been left with a complex history of multiple internal stratigraphic nomenclatures and philosophical diversity that have masked the inherent natural organization of the strata that make up the third-order Dinosaur Park-Bearpaw-Horseshoe Canyon sequence. This history has culminated in the present definitions whereby 1) the lower portion of the unit, which most geologists refer to (and study on field trips) as "Horseshoe Canyon" (well exposed at Willow Creek) is not exposed at all at the geographic location of Horseshoe Canyon; 2) the "Whitemud" and "Battle" units are separated by a regional subaerial unconformity and thus have different stratigraphic affinities: the Battle Formation is conformable with the overlying Scollard Formation and is not directly related to the Horseshoe Canyon Formation; 3) the Whitemud is not easily recognizable or regionally traceable in subsurface data and its uniquely recognizable characteristics result from pedogenic alteration beneath that unconformity; and 4) the "Horseshoe Canyon" is clearly subdivisible (as demonstrated in this report) into previously unrecognized, but regionally traceable, units in surface and subsurface data sets, which may be more useful in stratigraphic and resource potential analysis. To mitigate these problems, an effort is made in this report to resolve some stratigraphic questions.

The history of application of the stratigraphic nomenclature (Fig. 7) has culminated in the present confusion and dilemmas, as mentioned above, (Fig. 10, left side). One main purpose of this report is to attempt to resolve and correct these deficiencies, without undue upset of geologists' established usage, or proliferation of needless nomenclature. However, because the integrated synthesis and correlation of both outcrop and subsurface data allows a more complete vertical and lateral view of the strata, new informal subdivisions are suggested here for member-rank units of regional significance. These units, schematically illustrated in Figure 10 (right side), will aid in the important analysis of resource distribution and are detailed below.

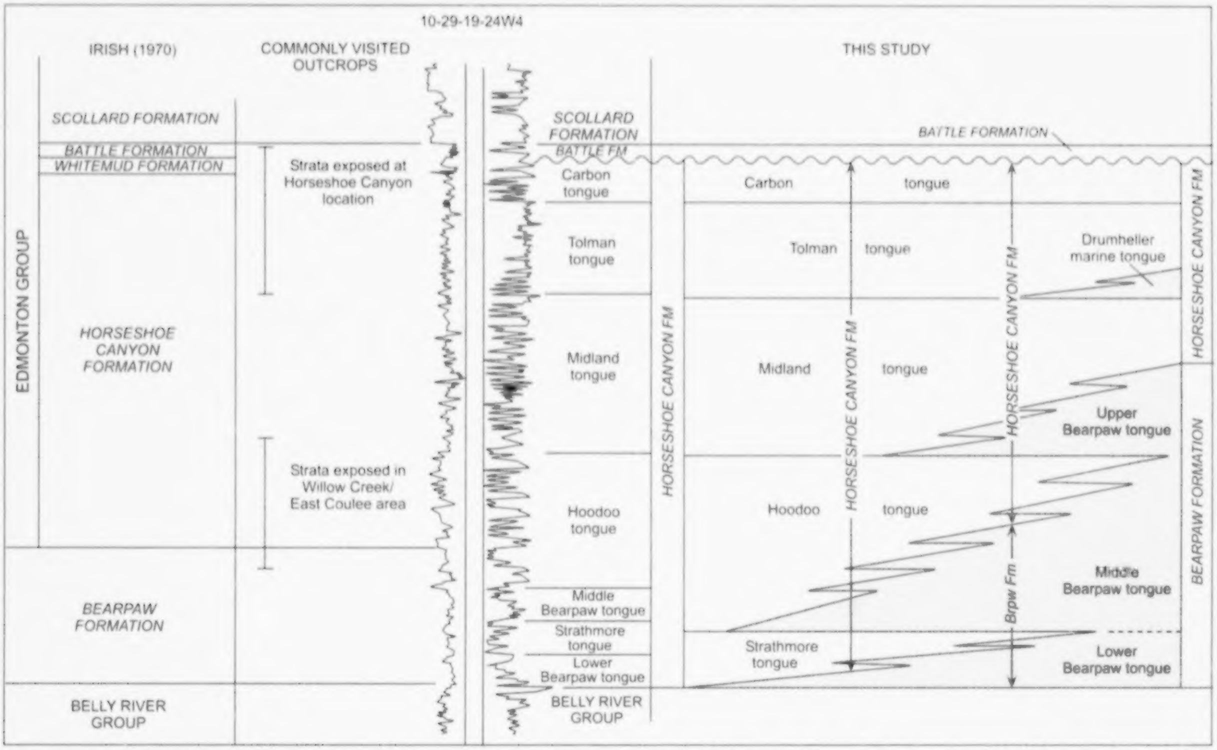


Figure 10. *Comparison of nomenclature of Irish (1970) vs. the framework established in this study, with an indication of the stratigraphic position of two often-visited and studied small outcrop areas where these rocks are commonly referred to as "Horseshoe Canyon". Note that the Bearpaw-Horseshoe Canyon contact is highly diachronous, rather than a fixed pick as previous workers implied, and depends on the interplay of geographic location vs. stratigraphic position.*

In previous studies, the Horseshoe Canyon Formation has been subdivided in several ways, using the Drumheller marine tongue (DMT) and Kneehills Tuff Zone (KTZ) as markers, illustrating complex relationships (Irish, 1970; Stelck et al., 1976). Ower (1960) identified several members, in ascending order: 1) Member A, 122–275 m, thickens rapidly to the north and west from 137 m at Drumheller to 222 m at Scollard Canyon, replacing upper Bearpaw Formation; 2) Member B, 61–91 m of green shale including the DMT at the base, 3) Member C, 21–55 m, including the Carbon-Thompson Coal Zone (Ower, 1960; Campbell, 1962; Yurko, 1975; Nurkowski, 1980) and 4) Member D, 6–15 m thick, which he termed the Battle/ Whitemud or KTZ. Similarly, McCabe et al. (1989) identified 1) the lower Horseshoe Canyon Formation with a "B-Zone marine shale", "lower tongue and basal coal zone", "Drumheller coal zone"; and 2) the upper Horseshoe Canyon Formation with a "Weaver coal zone" and a "Carbon-Thompson coal zone", all overlain by the Battle Formation.

My regional study, combining surface and subsurface data, of the upper Campanian–Maastrichtian Horseshoe Canyon Formation sandstone-dominated clastic wedge in the area of southern Alberta where it intertongues with the underlying Bearpaw Formation marine shale, has shown that it can be consistently subdivided into five, regionally extensive lithostratigraphic units, here designated as new informal units. For convenience, because the boundaries cannot currently be defined according to the requirements of NACSN (1983), and to minimize the impact on existing stratigraphic nomenclature, I recognize these units only as informal tongues that have discernible geometric relationships with marine tongues of the coeval Bearpaw Formation. Further work may establish more definitive boundaries and eventually suggest elevation to formal member rank at a later time. The treatment of all the units covered here is complicated by the intertonguing relationships with parts of the Bearpaw Formation.

Strathmore tongue (new informal unit)

Introduction

The Strathmore tongue represents the lowest sandy-coaly tongue of the Horseshoe Canyon Formation, extending southward and eastward into the lower portion of the Bearpaw marine shale. It does not outcrop in the study area and therefore was not recognized by Ower (1960) or Irish

(1970), but is easily identified on subsurface logs between tongues of marine shale, and pinches out to the east and southeast beneath the vicinity of the village of East Coulee. In the southeast portion of the study area, it is separated from the underlying Belly River Group by the lower Bearpaw marine tongue, and from the overlying Hoodoo tongue by the middle Bearpaw marine tongue. Its marine shale equivalent is assumed to be present in outcrops of the Bearpaw Formation southeast of the village of East Coulee where that portion of the stratigraphy rises to surface.

Definition and reference sections

The Strathmore tongue comprises thinly interbedded fine-grained sandstone, siltstone, carbonaceous mudstone and coal in a general coarsening-upward succession with intertonguing marine and nonmarine influence. The unit is nowhere exposed in outcrop, but is present in subsurface cores and logs throughout most of the study area, except for the southeastern corner. I propose a subsurface reference section in the continuous core of C.P.O.G. Strathmore 7-12-25-25W4, from a depth of 1660 to 1525 feet (506–465 m).

Name derivation

The Strathmore tongue is named after its occurrence in the C.P.O.G. Strathmore 7-12-25-25W4 well in the southeast part of the study area (Twp. 28, Rge. 25W4). Although this unit is nowhere exposed in surface outcrops, the southeastward pinch-out of the unit is situated in the subsurface beneath the East Coulee area.

Contacts, thickness, and regional extent

The Strathmore tongue is recognizable in the subsurface throughout the study area, except for the southeastern corner. The basal contact is a gradational intertonguing relationship with the underlying lower Bearpaw tongue of marine mudstone. The upper contact is an abrupt change in lithology from sandstone or coal to marine shale. This distinctive contact was referred to as the "E-marker" by McCabe et al. (1989). Within the study area, the Strathmore thickens to the west and northwest up to 111 m, but is generally 60 to 80 m thick. The unit pinches out to the southeast into marine shale to a zero edge along an irregular southwest-northeast line from Twp. 20, Rge. 22W4 to Twp. 28, Rge. 15W4.

Description

Sandstone: grey, very fine- to fine-grained; well sorted; in 0.5–3.0 m fining-upward beds; sharp bases and tops; some burrowing; horizontal lamination and ripple cross-lamination.

Mudstone: grey, sandy to muddy siltstone; thoroughly bioturbated near base, more carbonaceous near top.

Coal: numerous thin beds of carbonaceous mudstone and bituminous coal; up to 2 m thick; common rooted bases.

Age and correlation

The Strathmore tongue in the lower portion of the Horseshoe Canyon Formation and intertonguing with the lower portion of the Bearpaw Formation, is considered to be of late Campanian age. Because this unit is not present in surface exposures anywhere along the Red Deer River, it cannot be equated to any previous outcrop units, but represents the lowest nonmarine deposits of the Horseshoe Canyon Formation. It approximately correlates to the "lower tongue and basal coal zone" of McCabe et al. (1989).

Environment of deposition

Sediments of the Strathmore tongue were deposited in paralic settings as part of a coastal plain along the western and northwestern margin of the Bearpaw sea. Environments of deposition include shallow marine, shoreface, floodplain and swamp. Tidal influences may have occurred although there is no documented evidence for this aside from association with the overlying Hoodoo tongue. The lack of outcrop exposure limits the interpretation of this unit.

Hoodoo tongue (new informal unit)

Introduction

The Hoodoo tongue is the lowest sandy-coaly tongue of the Horseshoe Canyon Formation exposed in outcrop, intertonguing with the lower portion of the Bearpaw marine shale. It is well exposed in the Red Deer River valley between East Coulee and Drumheller, including at the well-known Hoodoos Provincial Recreation Area and adjacent Willow Creek, where numerous detailed sedimentological studies have been conducted over the last three decades. It is recognizable in the surface and subsurface throughout the study area and to the north and west, and is approximately equivalent to most of Member A of Ower (1960) and the lower Horseshoe Canyon Formation of Irish (1970). Coal Zones #0–7 of older literature are included in the Hoodoo tongue. In the southeast portion of the study area, it is separated from the underlying Strathmore tongue by the middle Bearpaw marine tongue, and from the overlying

Midland tongue by the upper Bearpaw marine tongue. The intertonguing of marine and nonmarine facies on a local scale is common in outcrops.

Definition and reference sections

The Hoodoo tongue comprises interbedded, thick, channelized sandstone, siltstone and abundant thick coal seams, reflecting marine tidal and nonmarine influences. The unit is well exposed in the Red Deer River valley between East Coulee and Drumheller. I propose a composite reference section on the valley wall at Hoodoos Provincial Recreation Area and adjacent Willow Creek, north of Highway 10, in Sec. 7, Twp. 28, Rge. 18W4, and adjacent Sec. 12, Twp. 28, Rge. 19W4. This site is easily accessible, displays a nearly complete section of the unit in three-dimensional outcrops that have been measured and studied many times by various authors (see references in Ainsworth, 1994). This site is therefore among the best known outcrop areas in central Alberta. I also propose a subsurface reference section in the continuous core of C.P.O.G. Strathmore 7-12-25-25W4, from a depth of 1418 to 1195 feet (432–364 m).

Name derivation

The Hoodoo tongue is named after the Hoodoos Provincial Recreation Area, located along the Red Deer River (Twp. 28, Rge. 18W5), at the mouth of Willow Creek, where the unit is well exposed. This site is regularly visited by geologists and laypersons alike, and is the most-studied site in the Red Deer River valley. The unit is well exposed in the Red Deer River and Willow Creek valley walls from the village of East Coulee to the city of Drumheller.

Contacts, thickness, and regional extent

The Hoodoo tongue is recognizable in the surface and subsurface throughout the study area and the southern Plains to the north and west. The unit is well exposed along the Red Deer River valley between East Coulee (Twp. 28, Rge. 18W4) and Drumheller (Twp. 29, Rge. 20W4). It is also exposed along Rosebud River near its confluence with the Red Deer (Twp. 28, Rge. 19W4). The basal contact displays a gradational intertonguing relationship with the underlying middle Bearpaw tongue of marine mudstone. The upper contact is an abrupt change in lithology from sandstone or coal to marine shale. Within the study area, the Hoodoo thickens to the west and northwest up to 146 m, but is generally 60 to 100 m thick. The unit thins to 10 to 20 m to the southeast, intertonguing with marine mudstone along an irregular southwest–northeast trend, suggesting the pinch-out zero edge is just beyond the data control in the southeast corner of the study area around Rge. 15W4. East of the Red Deer River valley there is little or no outcrop and all Horseshoe Canyon units are eroded away.

Description

Sandstone: pale grey, well sorted, very fine- to medium-grained; multistoried, fining-upward, scour-based bodies 1–10 m thick; trough-crossbedding, inclined heterolithic stratification, low-angle lamination.

Mudstone: greenish grey, muddy or sandy siltstone; fining-upward units up to 7 m thick; pedogenically homogenized and including sideritic concretion horizons toward the northwest; brownish grey with oyster shell fragments and burrows toward the southeast.

Coal: black, lignitic to bituminous coal and carbonaceous mudstone, in seams up to 3 m thick; sharp, rooted bases and tops, muddy partings; association with thick IHS sandstone.

Bentonite: pale greenish or brownish clay-rich mudstone; up to 1.5 m thick; uncommon, associated with coal.

Age and correlation

The Hoodoo tongue in the lower portion of the Horseshoe Canyon Formation, and intertonguing with the lower portion of the Bearpaw Formation, is considered to be of late Campanian age. This unit is approximately equivalent to the Blood Reserve Formation of southwestern Alberta, Member A of Ower (1960) and the "Coaly Member" of Srivastava (1968). It is also essentially correlative to the "Drumheller coal zone" of McCabe et al. (1989).

Environment of deposition and paleoflow

Sediments of the Hoodoo tongue were deposited in paralic settings as part of a coastal plain along the western and northwestern margin of the Bearpaw sea. Environments of deposition include shallow marine, shoreface, estuarine valley, floodplain and swamp. Tidal influences were prominent, as evidenced by the documented work of a number of authors in the Hoodoos, Willow Creek, and East Coulee area. Sediment dispersal was toward the southeast.

Midland tongue (new informal unit)

Introduction

The Midland tongue is the thick, middle, sandy-coaly tongue of the Horseshoe Canyon Formation, intertonguing with the middle Bearpaw marine shale. It is well exposed in the Red Deer River valley from Drumheller to Morrin Bridge, including at the famous Royal Tyrrell Museum of Paleontology and at Horsethief Canyon. It is recognizable in the surface and subsurface throughout the study area and to the north and west, and is approximately equivalent to the upper Member A and lower Member B of Ower (1960) and the middle Horseshoe Canyon Formation of Irish (1970). Coal Zones #8–10 of older literature are included in the Midland tongue. In the southeast portion of the study area, it is separated from the underlying Hoodoo tongue by the upper Bearpaw marine tongue, and from the overlying Tolman tongue by the Drumheller marine tongue. It is typified by nonmarine strata in outcrop, and is clearly less coaly than the Hoodoo tongue.

Definition and reference sections

The Midland tongue comprises thinly interbedded channelized sandstone, siltstone, and coal, with siltstone more dominant and coal less dominant than in the underlying Hoodoo tongue. These deposits reflect deposition in meandering fluvial channel and coastal floodplain overbank settings. The unit is well exposed in the Red Deer River valley from just east of Drumheller to north of Morrin Bridge as well as along Kneehills Creek and Rosebud River. I propose a composite reference section on the Red Deer River valley walls between Nacmine and Midland Provincial Park and Orkney Hill and Horsethief Canyon, along Highways 575 and 838, in Twp. 29 and 30, Rge. 20 and 21W4. This area is easily accessible, displays a nearly complete section of the unit in three-dimensional outcrops, includes the location of the Royal Tyrrell Museum of Paleontology and is often visited by geologists and laypersons alike. I also propose a main subsurface reference section in the continuous core of C.P.O.G. Strathmore 7-12-25-25W4, from a depth of 775 to 1195 feet (236–364 m).

Name derivation

The Midland tongue is named after Midland Provincial Park, a recreation area of natural and historical significance along the Red Deer River, just west of the City of Drumheller. The park includes the world-famous Royal Tyrrell Museum of Paleontology. The unit is well exposed in the valley walls in this area and toward the northwest as far as Morrin Bridge.

Contacts, thickness, and regional extent

The Midland tongue is recognizable in the surface and subsurface throughout the study area and the southern Plains to the north and west. The unit is well exposed along the Red Deer River valley between Drumheller (Twp. 29, Rge. 20W4) and just north of Morrin Bridge Provincial Recreation Area (Twp. 31, Rge. 21W4). It is also exposed along Rosebud River from the village of Rosedale (Twp. 28, Rge. 19W4) to Range Road 21-2 (Twp. 27, Rge. 21W4), and along Kneehills Creek from just east of the village of Dunphy to just east of the village of Hesketh (Twp. 29, Rge. 22W4). The basal contact reflects a gradational intertonguing relationship with the underlying upper Bearpaw tongue of marine mudstone (where it occurs), or a conformable contact with the Hoodoo tongue. The upper contact is an abrupt change in lithology from sandstone or coal to marine shale in the southeast, interpreted as a flooding surface, or to greenish siltstone-dominated strata in the northwest. Within the study area, the Midland thickens to the west up to 181 m, but is generally 100 to 120 m thick where mappable in subsurface logs. East of Rge. 21W4 the unit is behind surface casing in most wells and little data is available regarding thickness and distribution. East of the Red Deer River valley there is little or no outcrop and all Horseshoe Canyon units are eroded away.

Description

Sandstone: pale grey, well sorted, very fine- to coarse-grained; multistoried, fining-upward, scour-based units up to 6 m thick; trough-crossbedding, low-angle lamination, ripple crosslamination and inclined bedding; rare IHS near base and top.

Mudstone: greenish grey, sandy siltstone; fining-upward units up to 4 m thick; pedogenically homogenized with sideritic concretion horizons; thin carbonaceous partings.

Coal: black, lignitic to bituminous coal and carbonaceous mudstone seams up to 2 m thick; sharp, rooted bases and tops, minor muddy partings.

Bentonite: pale grey or brownish clay-rich siltstone; up to 1.5 m thick; uncommon, associated with pedogenic siltstone.

Age and correlation

The Midland tongue in the middle portion of the Horseshoe Canyon Formation and intertonguing with the middle portion of the Bearpaw Formation, is considered to be of latest late Campanian age. This unit is approximately equivalent to the lower portion of Member B of Ower (1960) and the "Non-coaly Member" of Srivastava (1968). The Midland tongue is approximately correlative to the "Weaver coal zone" of McCabe et al. (1989).

Environment of deposition and paleoflow

Sediments of the Midland tongue were deposited in paralic to floodplain settings as part of a coastal plain along the western and northwestern margin of the Bearpaw sea. Environments of deposition include shoreface, estuarine valley, fluvial channel, floodplain and swamp. Sediment dispersal was toward the east-southeast.

Tolman tongue (new informal unit similar to a unit informally defined by Srivastava, 1968)

Introduction

The Tolman tongue is a unit in the upper part of the Horseshoe Canyon Formation dominated by greenish siltstone with little or no coal. The lack of coal is conspicuous in both surface outcrops and in subsurface logs, and is paramount in identifying this unit. At its base is the well-known Drumheller marine tongue (DMT) but the bulk of the tongue consists of nonmarine pedogenic deposits. It is well exposed in the Red Deer River valley between Bleriot Ferry and Dry Island Provincial Park. It is recognizable in the surface and subsurface throughout the study area and to the north and west, primarily by the uniform fine grain size and lack of coal. The Tolman is approximately equivalent to most of Member B of Ower (1960) and the middle Horseshoe Canyon of Irish (1970). It is similar in stratigraphic position and lithology to, but more inclusive than, the "Tolman member" of Srivastava (1968), which was never formally defined in an adequate fashion. In the southeast portion of the study area, it is separated from the underlying Midland tongue by the Drumheller marine tongue, and is overlain sharply by the Carbon tongue. The identification of this distinctive unit, both in outcrop and subsurface data, was key to realizing the regional subdivisibility of the Horseshoe Canyon Formation.

Definition and reference sections

The Tolman tongue comprises greenish grey, pedogenic siltstone and thin to thick splay and channel sandstone interbeds, with virtually no coal or carbonaceous mudstone. The unit is well exposed in the Red Deer River valley from Bleriot Ferry to north of Dry Island Provincial Park, as well as along Kneehills Creek (including at Horseshoe Canyon) and Rosebud River. I propose a composite reference section in the vicinity of Tolman Bridge and southward on the Red Deer River at Twp. 32 and 33, Rge. 21 and 22W4. I also propose a composite outcrop reference section on the valley walls of the tributaries of Kneehills Creek, which form the well-known Horseshoe Canyon Provincial Recreation Area, beside Highway 9, 15 km west of Drumheller, in Sec. 3, 4, and 9 Twp. 28, Rge. 21W4. In addition, I propose a main subsurface reference section in the continuous core of C.P.O.G. Strathmore 7-12-25-25W4, from the top of the core to a depth of 770 feet (and on the accompanying log from 480–770 feet; 146–235 m).

Name derivation

The name for the Tolman tongue is derived from that originally proposed by Srivastava (1968) for these strata, and for the vicinity where they are best exposed at Tolman Bridge on the Red Deer River.

Contacts, thickness, and regional extent

The Tolman tongue is recognizable in the surface and subsurface throughout the study area and the southern Plains to the north and west. The unit is well exposed along the Red Deer River valley between Bleriot Ferry (Twp. 30, Rge. 21W4) and Dry Island Provincial Park (Twp. 34, Rge. 21W4). It is also exposed along Kneehills Creek from just east of the village of Hesketh (Twp. 29, Rge. 22W4) to just east of the village of Carbon (Twp. 29, Rge. 23W4) and, along Rosebud River from Range Road 21-2 to just east of the village of Rosebud (Twp. 27, Rge. 21W4). The basal contact reflects a gradational intertonguing relationship with the underlying Drumheller marine tongue (where it occurs), or a conformable contact with the Midland tongue. The upper contact is an abrupt change in lithology from greenish siltstone to the sandstone, mudstone and thick coal seams of the overlying Carbon tongue. Within the study area, the Tolman thickens to the west up to 125 m, but is generally 70 to 100 m thick where mappable in subsurface logs. East of Rge. 22W4 the unit is behind surface casing in most wells and little data is available regarding thickness and distribution. East of the Red Deer River valley there is little or no outcrop and all Horseshoe Canyon units are eroded away.

Description

Siltstone: greenish grey, commonly sandy, may fine upward, or not; in units up to 15 m thick, commonly with thin, sandy interbeds; pedogenically homogenized with abundant, thin, sideritic concretion horizons; rare dark mudstone with oyster shells near base.

Sandstone: pale grey, well sorted, very fine- to medium-grained in fining-upward scour-based units up to 6 m thick; may be thick, extensive and multistoried, or thin lenses which, are laterally discontinuous and with gradational boundaries; trough-crossbedding, ripple crosslamination, low-angle lamination; rare IHS near base.

Coal: coal and carbonaceous mudstone seams rare and thin, up to 50 cm.

Sandy limestone: laterally continuous sideritic sandy limestone deposits up to 1 m thick, with roots, gradational bases and sharp irregular tops, common in upper part; sandy limestone with in situ oyster shells, *Planolites* and *Skolithos* burrows, present near base.

Age and correlation

The Tolman tongue in the middle to upper portion of the Horseshoe Canyon Formation, and intertonguing with or overlying the Drumheller marine tongue, is considered to be of earliest Maastrichtian age. This unit is similar to the upper portion of Member B of Ower (1960), the "green siltstone unit" of Gibson (1977) and the "fine-grained unit" of Nurkowski and Rahmani (1984). It is also similar in lithology and stratigraphic position to the "Tolman member" of Srivastava (1968). However, the definition suggested by Srivastava (1968) was included in a thesis (which is inadequate publication according to NACSN, 1983), and the lower boundary was inadequately defined for utility beyond the immediate location. The Tolman tongue as used in this study includes the 40 m section that Srivastava studied at Tolman Bridge plus other strata with similar lithologies exposed at other sections and in the subsurface.

Environment of deposition and paleoflow

Sediments of the Tolman tongue were deposited in floodplain settings as part of a vast coastal plain along the western and northwestern margin of the Bearpaw sea. Environments of deposition include fluvial channel, floodplain, overbank and paleosols. Sediment dispersal was toward the east-southeast.

Carbon tongue (new informal unit)

Introduction

The Carbon tongue is the uppermost sandy-coaly tongue of the Horseshoe Canyon Formation, and does not intertongue with the Bearpaw marine shale in the study area. It is well exposed in the Red Deer River valley from north of Morrin Bridge to north of Dry Island Provincial Park. It is recognizable in the surface and subsurface to the north and west. The Carbon is approximately equivalent to Members C and part of D of Ower (1960) and the upper Horseshoe Canyon and Whitemud formations of Irish (1970). Coal Zones #11 and 12 ("Carbon" and "Thompson") of older literature are included in the Carbon tongue. It sharply overlies the underlying Tolman tongue, and is overlain sharply (unconformably) by the Battle Formation. The coaly nature of this unit, positioned above the non-coaly Tolman tongue, is easy to identify in outcrop and subsurface work.

Definition and reference sections

The Carbon tongue comprises thickly interbedded sandstone, siltstone, and coal, with a very distinctive white sandstone unit at the top. These deposits represent deposition on a fluvial floodplain. The unit is well exposed in the Red Deer River valley from north of Morrin Bridge to north of Dry Island Provincial Park, as well as along Kneehills Creek in the vicinity of the village of Carbon and along Rosebud River. I propose a composite reference section on the valley walls of the Red Deer River in the vicinity of Tolman Bridge, beside Highway 585, in Twp. 33, Rge. 22W4. This area is easily accessible and displays a complete section of the unit in three-dimensional outcrops. I also propose a composite outcrop reference section on the valley walls of the tributaries of Kneehills Creek, which form the well-known Horseshoe Canyon Provincial Recreation Area, beside Highway 9, 15 km west of Drumheller, in Sec. 3, 4, and 9, Twp. 28, Rge. 21W4. This area is easily accessible, displays a complete section of the unit in 3-dimensional outcrops and is regularly visited by geologists and laypersons alike. The Carbon tongue is poorly represented in subsurface logs of the study area because its shallow depth places it behind surface casing in most wells. However, a subsurface reference section at 14-5-35-27W4, at a depth of 310 to 455 m, displays the characteristics well. The Carbon tongue is not present in the cored interval of C.P.O.G. Strathmore 7-12-25-25W4, but is recorded on the accompanying log from 350 to 480 feet (107–146 m).

Name derivation

The Carbon tongue is named after the village of Carbon, Alberta, located on Kneehills Creek in Twp. 29, Rge. 23W4 where this seam was mined, and for the traditional name of one of the included extensively mined coal seams in the area, the "Carbon Seam". The unit is well exposed in the valley walls of Kneehills Creek from Horseshoe Canyon to Carbon and those of Red Deer River from Morrin Bridge to Dry Island.

Contacts, thickness, and regional extent

The Carbon tongue is recognizable in the surface and subsurface throughout the western portion of the study area and the southern Plains to the north and west. The unit is well exposed along the Red Deer River valley from north of Morrin Bridge (Twp. 31, Rge. 21W4) to north of Dry Island Provincial Park (Twp. 34, Rge. 21W4). It is also exposed at Horseshoe Canyon and along Kneehills Creek from Appleyard Coulee to west of the village of Carbon, near Highway 21 (Twp. 29, Rge. 22/23W4) and along Rosebud River east of the village of Rosebud (Twp. 27, Rge. 21W4). The basal contact is a conformable contact with the Tolman tongue. The upper contact is an abrupt, disconformable surface with a change in lithology from thick sandstone, siltstone, and coal to black, organic-rich, bentonitic mudstone of the overlying Battle Formation or brownish-yellowish coarser sandstone and varicoloured mudstone of the overlying Scollard Formation. Within the study area, the Carbon thins and thickens irregularly in the 50 to 80 m range, but is up to 101 m thick. East of Rge. 25W4 the unit is behind surface casing in most wells and little data is available regarding thickness and distribution. At the outcrops along the Red Deer River and at Horseshoe Canyon its thickness ranges from 45 to 60 m. East of the Red Deer River valley there is little or no outcrop and all Horseshoe Canyon units are eroded away.

Description

Sandstone: pale grey, well sorted, very fine- to coarse-grained, in multistoried, scour-based, fining-upward units 1 to 7 m thick; trough-crossbedding, ripple crosslamination, low-angle lamination, inclined bedding; distinctive white sandstone bodies 3 to 7 m thick near top (Whitemud sandstone).

Siltstone: greenish grey to dark grey, muddy or sandy siltstone in fining-upward units up to 4 m thick; pedogenically homogenized with thin, dispersed sideritic concretion horizons.

Coal: black lignitic to bituminous coal and carbonaceous mudstone in abundant seams up to 2 m thick; sharp rooted bases and tops, minor muddy partings.

Age and correlation

The Carbon tongue, in the upper portion of the Horseshoe Canyon Formation, is considered to be of early Maastrichtian age. This unit is approximately equivalent to Members C and part of D of Ower (1960), the Coaly Member/Whitemud Member of Srivastava (1968) and the Carbon-Thompson coal zones of Narkowski (1980) and McCabe et al. (1989).

Environment of deposition and paleoflow

Sediments of the Carbon tongue were deposited in floodplain settings as part of a vast coastal plain along the western and northwestern margin of the Bearpaw sea. Environments of deposition include fluvial channel, floodplain, overbank and swamp. Sediment dispersal was toward the east.

THREE-DIMENSIONAL GEOMETRY AND DISTRIBUTION

Surface and subsurface correlation

The Horseshoe Canyon Formation and its constituent members are extensively exposed along the valley walls of the Red Deer River, and its tributaries, in south-central Alberta, in the vicinity of the City of Drumheller (Twp. 27–38, Rge. 18–23W4), the outcrop area described in this report. In any chosen area, subsurface study of the Horseshoe Canyon Formation is greatly assisted by the presence of the regionally recognizable characteristics of its well-log signature and the presence of significant nearby outcrops and core, which together allow integrated analysis of the regional framework of the wedge. This was illustrated by Hamblin (1998a, d) for areas south of the current study, where Horseshoe Canyon and St. Mary River facies apparently intertongue. Although many of the characteristics described below are discernible in outcrop in the Red Deer River valley, the regional cross-sectional geometry is best depicted by the long vertical sections afforded by subsurface data, which can then be correlated and ground-checked through outcrop data (Fig. 11). In fact, the newly-identified Strathmore tongue is *only* identifiable in subsurface data. Figure 10 illustrates the internal stratigraphic subdivision of the Horseshoe Canyon Formation, and the distinctive gamma ray-porosity log characteristics of the component parts. The thinly interbedded nature of the various lithologies and the abundance of coal in several zones is obvious. Likewise, the intertonguing of Bearpaw marine shale with these lithologies at the base of the formation is clear, a relationship also emphasized by McCabe et al. (1989). The gamma ray-porosity log cross-sections in this report use the regionally recognized "top of Belly River Group" as a datum. This datum marks the top of the Dinosaur Park transgressive depositional succession (see Hamblin and Abrahamson, 1996; Hamblin, 1997a, b) and the base of the Bearpaw-Horseshoe Canyon regressive depositional succession. The distinct geophysical log signature of this surface is recognizable and correlatable over most of southern Alberta and Saskatchewan. In the study by McCabe et al. (1989), this surface was referred to as the "A-

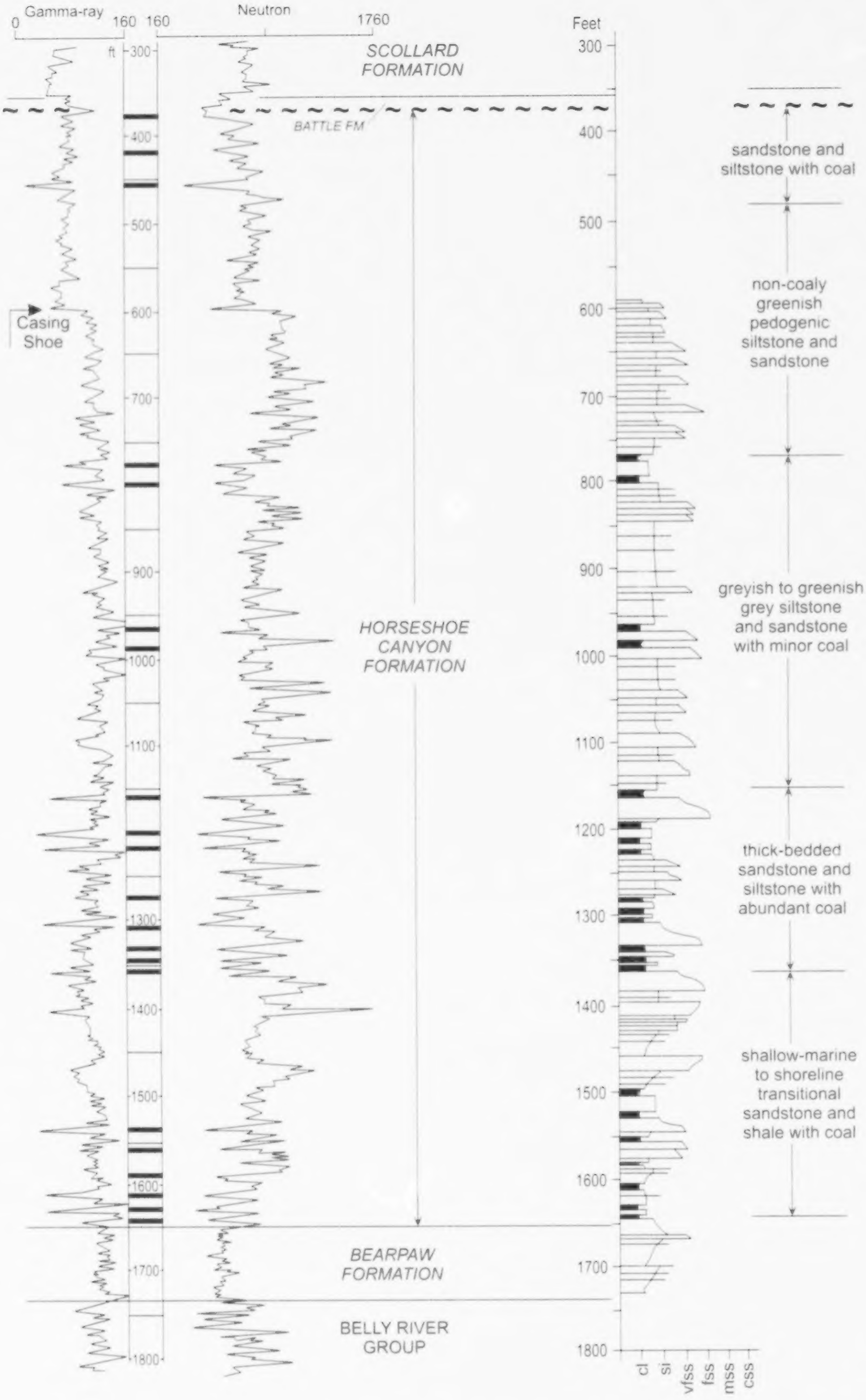


Figure 11. *Subsurface gamma-ray-neutron log and simplified core description for C.P.O.G. Strathmore EV 7-12-25-25W4 core (from Hamblin, 1998c).*

top". Although this may not represent a truly horizontal datum and may not coincide exactly with the maximum flooding surface in all locations, it is the most practical approximation. It is noteable that the Lethbridge Coal Zone is always developed at the top of the Belly River Group, clearly associated with the rapid base level rise and extensive marine flooding of the Bearpaw Formation, as discussed by Hamblin (1997b).

The Horseshoe Canyon Formation, and the five constituent tongues generally thin toward the east and southeast as they intertongue with Bearpaw marine shale. The northern and northwestern limits beyond the scope of this study area are, as yet, unresolved.

7-12-25-25W4

The continuous core from the Canadian Pacific Oil and Gas Ltd. Strathmore EV 7-12-25-25W4 well, located about 40 km east of Calgary (Fig. 12), was drilled in 1968 in the present study area. It is the most complete subsurface record of Campanian–Maastrichtian strata in the basin. Hamblin (1998c) provided a detailed description of the lithologies and facies present. The cored section of upper Campanian–Maastrichtian rocks covers about 1130 feet (344 m), missing only the upper 250 feet (76 m) of the Horseshoe Canyon (Carbon tongue), which however is present on the accompanying gamma ray-porosity log. This core displays the lower four of the five tongues delineated in this study, allowing direct lithological correlation with the outcrop belt to the east (Fig. 13), and illustrating the lithofacies and geophysical signatures of the units.

Regional cross-sectional geometry and correlation

Detailed west-east gamma ray-porosity log cross-sections were constructed for each Township in the study area. The general west-east gamma ray-porosity log sections included

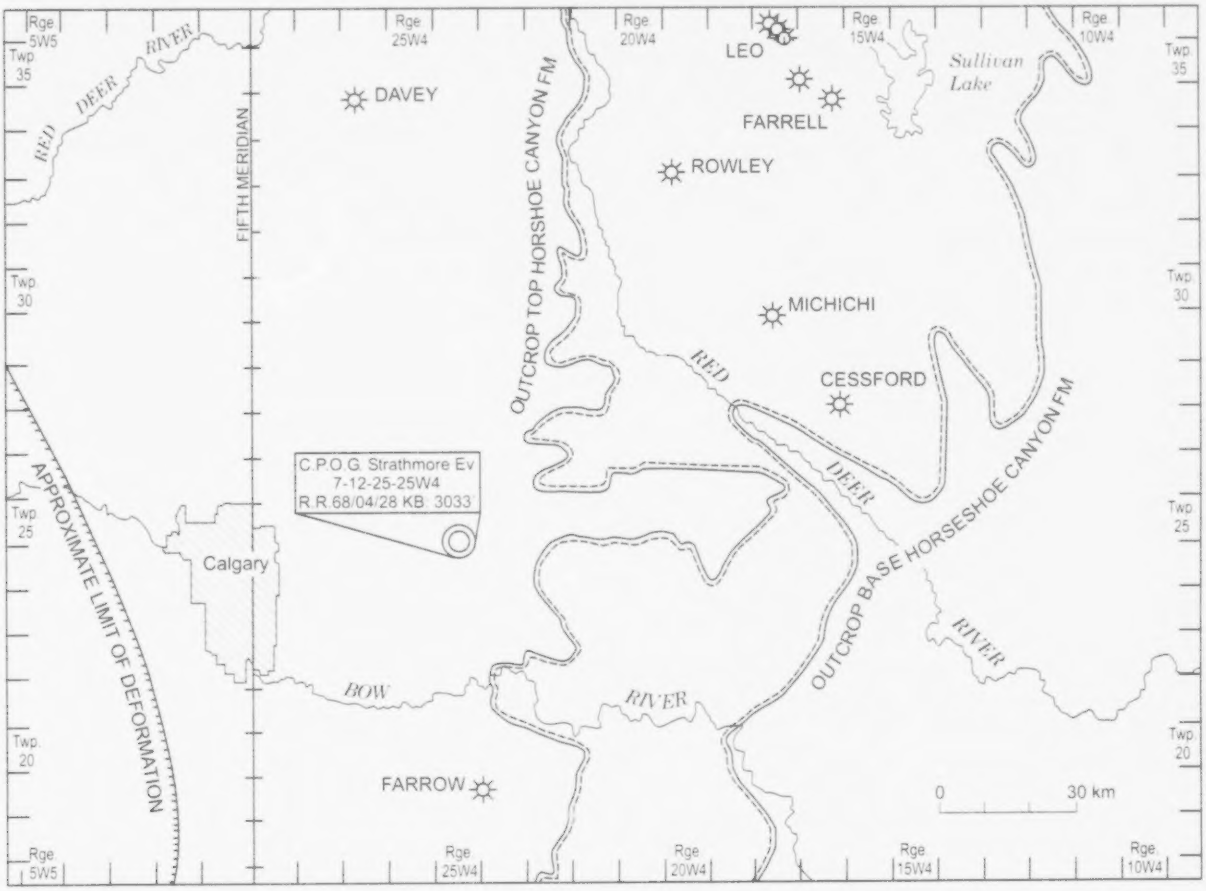


Figure 12. *Location of C.P.O.G. Strathmore EV 7-12-25-25W4 core. Outcrop limits of Horseshoe Canyon Formation and nearby Horseshoe Canyon gas pools are indicated (from Hamblin, 1998c).*

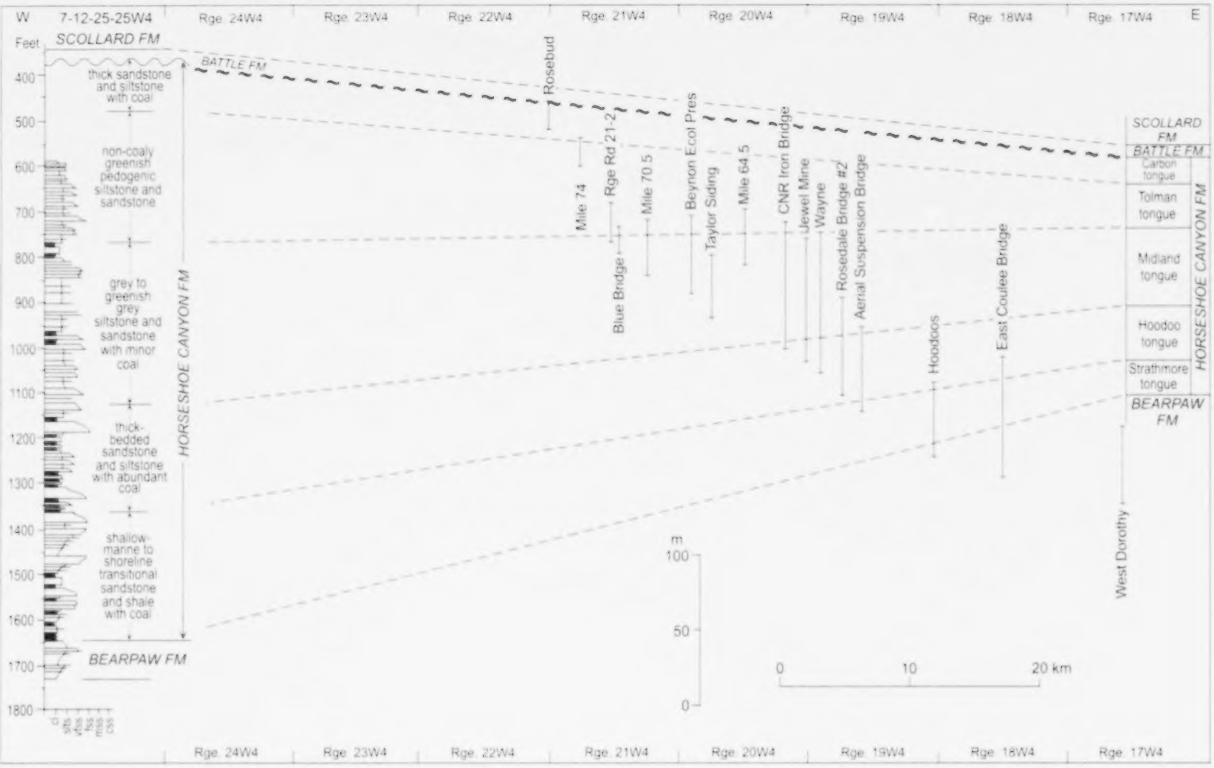


Figure 13. Comparison of measured core section from C.P.O.G. Strathmore EV 7-12-25-25W4 well with measured outcrop sections from the Red Deer and Rosebud rivers, including correlation of new information units (modified from Hamblin, 1999).

here (Fig. 14, 15, 16, on CD-ROM in pocket) have been simplified from original one-well-per-Township working sections hung on the "top of Belly River" datum. Correlations were made on the many original detailed sections and then transferred to the examples here, hence some detail of internal complexities is lost in these displays through the omission of intervening wells. However, it serves to illustrate the gross cross-sectional characteristics of the formation and tongues in three dimensions and at a regional scale.

The entire Horseshoe Canyon Formation thins dramatically to the south and southeast in the area of southern Alberta for which subsurface data is available. This is due primarily to regional thinning from the base, where the sandstone-dominated subdivisions pass basinward into marine shale of the Bearpaw Formation. In the search for some consistent, and practically applicable, internal organization to these upper Campanian–Maastrichtian strata, an empirical subdivision based on the presence of several, nonmarine, sandy-coaly correlatable, member-scale subunits, separated by thinner marine shale units, became apparent. The most obvious stratigraphic relation depicted on the cross-sections is the intertonguing of Bearpaw Formation marine shale tongues (dominant in the east and south) with Horseshoe Canyon Formation, sandy, nonmarine tongues (dominant in the west and north), especially in the lower half of the formation. These relationships define the Horseshoe Canyon tongues defined above, and described in more detail below.

These nonmarine to marginal marine tongues of the Horseshoe Canyon Formation are characterized by thinly interbedded sandstone, siltstone and coal, expressed as sharply serrated, but generally low-value gamma-ray log signatures. The very low gamma-ray and high porosity readings of coal seams are diagnostic in most cases. These characteristics are in stark contrast to the more uniform, less "active", higher gamma-ray and porosity readings typical of the intertonguing marine shale units. These contrasting log signatures can be correlated systematically from well to well along the cross-sections.

The sandstone- and coal-dominated units represent Horseshoe Canyon Formation nonmarine to marginal-marine facies, generally have gradational bases, sharp, flat tops, and thin to the south and east, primarily from the base. These units appear to extend to ultimate pinch-out limits beyond the study area data control to the east. In contrast, the shale-dominated units, representing Bearpaw Formation marine facies, generally have sharp, flat bases, more gradational tops, and thin to the north and west, primarily from the top. McCabe et al. (1989) also identified several of these marine, shale-dominated units in the lower part of the succession as the "B-zone (lower Bearpaw)" and "upper Bearpaw". The ultimate pinch-out limits of most of these shaly units is recorded in the data of this study area. Overall, each successively younger sandy-coaly Horseshoe Canyon tongue extends farther southward and eastward, whereas each successively younger, shaly Bearpaw tongue extends less far to the north and west. This geometric relationship depicts the general coarsening-upward, progradational nature of the Bearpaw-Horseshoe Canyon regressive depositional system.

In studying the coals of the lower Horseshoe Canyon Formation of the Red Deer River valley, McCabe et al. (1989) identified a succession of correlatable units that relate well to those described in this study. These are as follows: 1) their "B-zone" lowest marine shale correlates to my "lower Bearpaw tongue"; 2) their "lower tongue and basal coal zone" correlates to my "Strathmore tongue", and their "E-marker" equates to the flooding surface capping the Strathmore; 3) their "upper Bearpaw" correlates to my "middle Bearpaw tongue", presumably because they did not identify a higher marine tongue; 4) their "Drumheller coal zone" is similar to my Hoodoo tongue"; and 5) their "Weaver coal zone" relates to part of my "Midland tongue".

The tops of the sandy-coaly Horseshoe Canyon tongues are essentially flat relative to the top of Belly River datum used and are sharply overlain by marine shale tongues. These shaly tongues pass gradationally upward into the succeeding sandy-coaly tongue, suggesting the presence of multiple cycles, essentially coarsening-upward successions, passing from shale-dominated to sandstone-dominated, and having regional extent. Lower marine shaly portions rest abruptly on previous cycles and thicken to the south and east (basinward), whereas the gradationally overlying upper sandy-coaly portions thicken to the north and west (sourceward). The four, stacked, coarsening-upward cycles are represented by 1) lower Bearpaw tongue-Strathmore tongue (B-zone–lower tongue and basal coal zone of McCabe et al., 1989), 2) middle Bearpaw-Hoodoo tongue (upper Bearpaw–Drumheller coal zone of McCabe et al., 1989), 3) upper Bearpaw tongue-Midland tongue (Weaver coal zone of McCabe et al., 1989), 4) Drumheller marine tongue-Tolman tongue, and 5) Carbon tongue (Carbon–Thompson coal zone of McCabe et al., 1989). These cycles are discussed in much greater detail below. It is clear that, over a lateral distance of 100+ km, each cycle becomes more shaly to the south and east (basinward) and overlies and extends farther south and east (basinward) than the preceding one. For convenience and pragmatism in this study I have defined the cycle boundaries at the sharp tops of the mappable sandstone- and coal-dominated tongues. These sharp, flat, contacts between coal-bearing sediments below and marine shale above are considered to represent flooding surfaces within the predominantly nonmarine Horseshoe Canyon clastic wedge, confirmed by actual rock observations described below. Thus these cycles are primarily characterized by regressive successions that gradationally pass laterally into the equivalent portions of the Bearpaw Formation marine shale to the south and east.

It is also clear that each cycle is actually a composite of thinner, individual, generally coarsening-upward, fifth-order subunits that mimic the southward and eastward thinning and fining trends of the larger cycles. Over large lateral distances these individual subunits pass from sandy-coaly facies within the Horseshoe Canyon Formation to marine shaly facies within the Bearpaw Formation as they thin and fine to the south and east. These fifth-order regressive cycles have more localized extents but could be mapped separately. They are essentially equivalent to the stacked, multiple sequences identified at Willow Creek (all within the Hoodoo tongue), and studied in detail by Shepheard and Hills (1970), Rahmani (1983), Saunders (1989), Ainsworth (1994) and Lavigne (1999). Those identified here also include the "coarsening-upward successions" emphasized by McCabe et al. (1989).

From the foregoing discussion it is clear that the specific "Bearpaw-Horseshoe Canyon transition" studied in such detail in the East Coulee-Willow Creek area over many decades, is only one of several stacked "Bearpaw-Horseshoe Canyon transitions" that occur in the upper Campanian–Maastrichtian strata of south-central Alberta (due to diachroneity of this contact), each with similar characteristics. The first empirical step of recognizing, delineating, mapping, and interpreting these regionally extensive Horseshoe Canyon tongues, fourth-order, and fifth-order cycles is very useful in focussing attention on several scales of reservoir trends and the limits of the various depositional systems.

Distribution and plan-view geometry

Thicknesses for each sandy tongue in the Horseshoe Canyon Formation and the intertonguing Bearpaw marine units were plotted and contoured at 10 m intervals across the study area, primarily using subsurface data (Fig. 17–25). The results constitute generalized maps at a regional scale that display the three-dimensional extent and geometrical interrelationships of the Horseshoe Canyon-Bearpaw depositional system. Maps at this scale mask the undoubtedly complex internal geometric details, and are meant only to illustrate the gross characteristics and distribution of the intertonguing units. For example, in the Hoodoo tongue, we know from detailed sedimentological studies that multiple localized marine tongues exist in the outcrop in the type area at Willow Creek, and divide this tongue into multiple, stacked fifth-order subunits.

Clearly, the nonmarine sandy tongues (supplied from the northwest) extended progressively farther southeastward throughout deposition of the Horseshoe Canyon Formation. Concomitantly, the successive Bearpaw marine tongues (reaching from the southeast) extended progressively less far northwestward through time. These relationships are illustrated by the cross-sections and by the southeastward shift of zero deposition lines and loci of thicknesses upward through the Horseshoe Canyon Formation. In addition, within the depositional area for each tongue, there are obvious linear trends of thicker deposition 10 to 20 km wide, separated by thinner areas. In most Horseshoe Canyon tongues, these linear isopach trends have a northwest-southeast or west-east orientation, and the locations appear to be relatively stable through time. Likewise, intervening Bearpaw tongues display inverse linear thicks and thins that match in location those of the overlying sandy formation. These relations suggest that sandy depositional input was primarily from the west or northwest in large distributary valleys that persisted through time, but was variable, allowing a stacked pattern of regression and transgression. Also, the locus of the nonmarine-marine interface shifted southeastward with each successive regional-scale transgression or regression.

Isopach maps

The lower Bearpaw marine tongue (Fig. 17) is thickest to the southeast (50–70 m), the direction from which interpreted marine incursion proceeded, and thins dramatically to the northwest and west (to 0 m) over about 100 km of lateral distance. Based on the subsurface cross-sections, this thinning takes place from the top. To the southeast the tongue merges with the main body of Bearpaw Formation marine shale deposits. This unit does not outcrop within the study area, but presumably forms the lower portion of the Bearpaw mapped at the surface to the southeast. The zero pinchout occurs in the subsurface along a nearly north-south line roughly from Red Deer to Calgary. The distinct northwest-southeast-trending areas of thin marine shale deposition approximately match thick trends in the overlying Strathmore tongue.

During deposition of the Strathmore tongue (Fig. 18), sandy input was derived mainly from the west and northwest, and thicknesses reach 90 m. It spread eastward and southeastward to the East Coulee-Hanna area. According to the subsurface cross-sections, thinning toward the southeast is from the base. The zero pinchout occurs along a northeast-southwest-trending line drawn roughly from Castor to Hanna to Cluny. Therefore, this unit does not outcrop in the study area because it pinches out in the subsurface just before rising to the surface. Distinct northwest-southeast or west-east trending depositional thicks are interpreted to generally mark the loci of sediment dispersal.

The middle Bearpaw marine tongue (Fig. 19) displays depositional characteristics similar to those of the lower tongue. The clear northwestward thinning reaches a zero pinchout along a line from east of Red Deer to the east side of Calgary, and thickens to the southeast to more than 100 m where it merges into the main body of Bearpaw marine shale. The position of the zero pinchout is 10 to 20 km eastward of, and the thicknesses recorded in the study area are 20 to 30 m greater than, those for the lower Bearpaw tongue, illustrating the southeastward stepping of depositional loci with each successive transgressive-regressive cycle. Thinning toward the northwest occurs from the top. This unit outcrops only in the vicinity of the West Dorothy, East Coulee, and Hoodoos sections in this study area. Distinct trends of thinness correspond roughly to similar trends of thickness in the overlying Hoodoo tongue.

The Hoodoo tongue (Fig. 20) displays similar relations to those expressed by the Strathmore tongue, but translated geographically to the southeast. Sandy input was derived mainly from the west and northwest, and spread eastward and southeastward to a zero pinchout in the Hanna-Bassano area, just at the eastern boundary of the database and the study area. Based on subsurface cross-sections, the thinning takes place from the base of the unit toward the southeast. The unit occurs in outcrop at all sections on the Red Deer River between East Coulee and Drumheller, and on the Rosebud River between its confluence with the Red Deer River and Wayne, and represents one of the main coal-bearing portions of the Horseshoe Canyon Formation. This unit comprises the bulk of the deposits that have been intensively studied by so many geologists in the Hoodoos, Willow Creek, and East Coulee areas (see previous discussions). Those studies have identified large, southeast-trending estuarine channels near the marine-nonmarine interface; the current mapping indicates that shoreline interface was several tens of kilometres distant to the southeast. Thicknesses are up to about 130 m along the 5th meridian and west-east linear thickness trends of 100 m commonly extend outward many tens of kilometres.

The upper Bearpaw marine tongue (Fig. 21), composed primarily of shale, displays depositional characteristics similar to those of the lower and middle tongues. The clear northwestward thinning reaches a zero pinchout along a line from Alix to Carbon to Strathmore, and thickens to the southeast to at least 60 m before the surface and subsurface

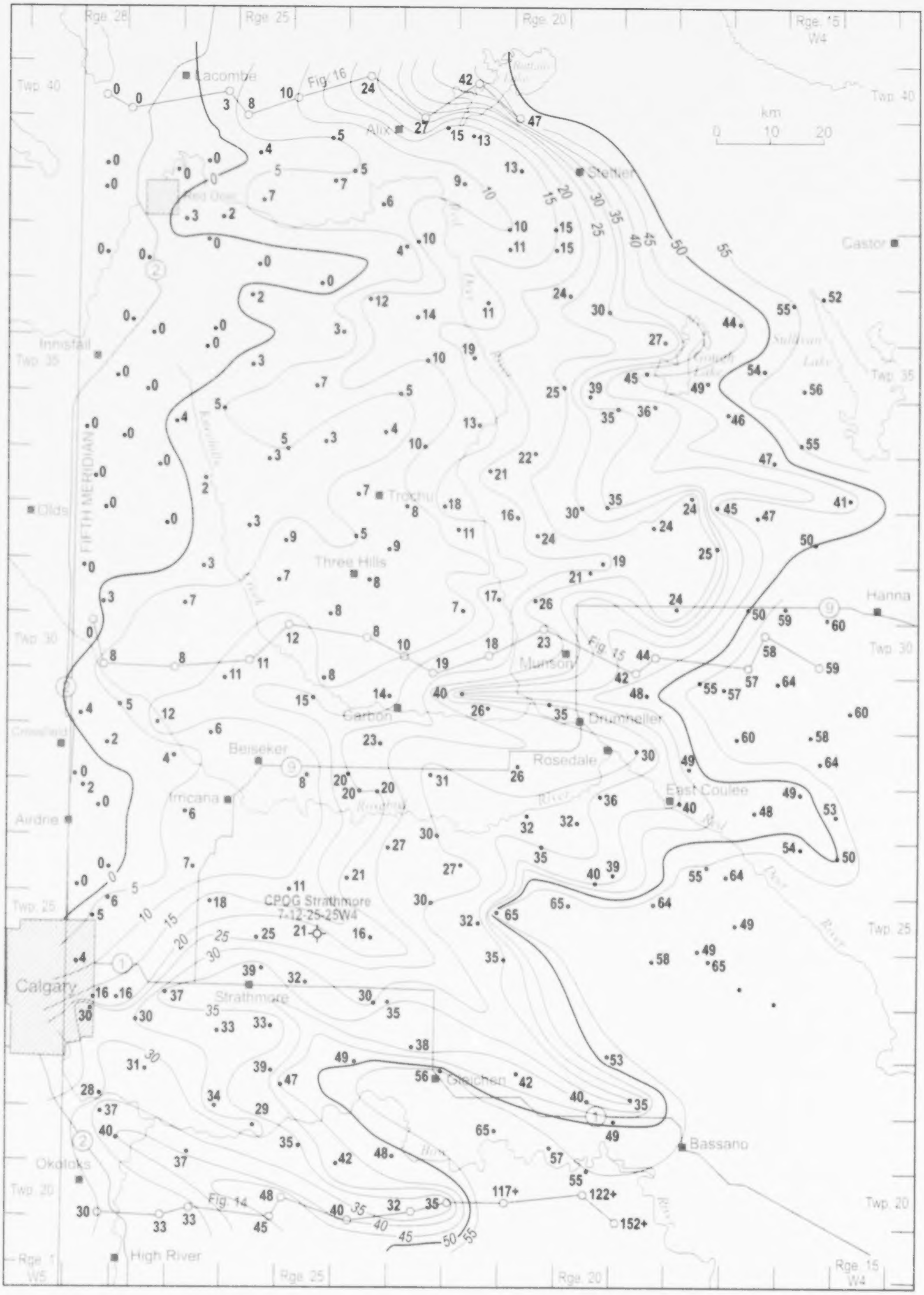


Figure 17. Isopach (in metres) of lower Bearpaw tongue.

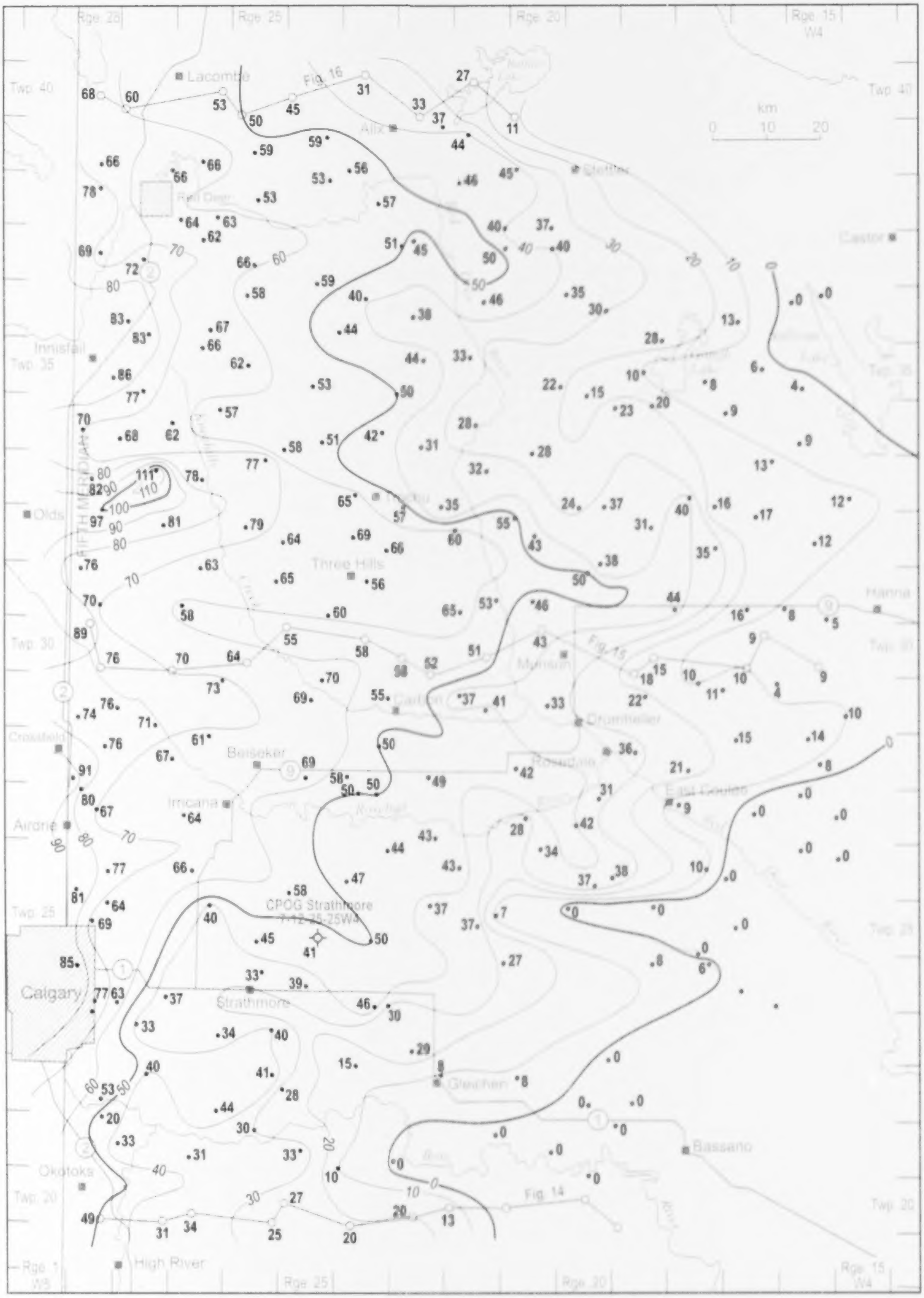


Figure 18. Isopach (in metres) of Strathmore tongue.

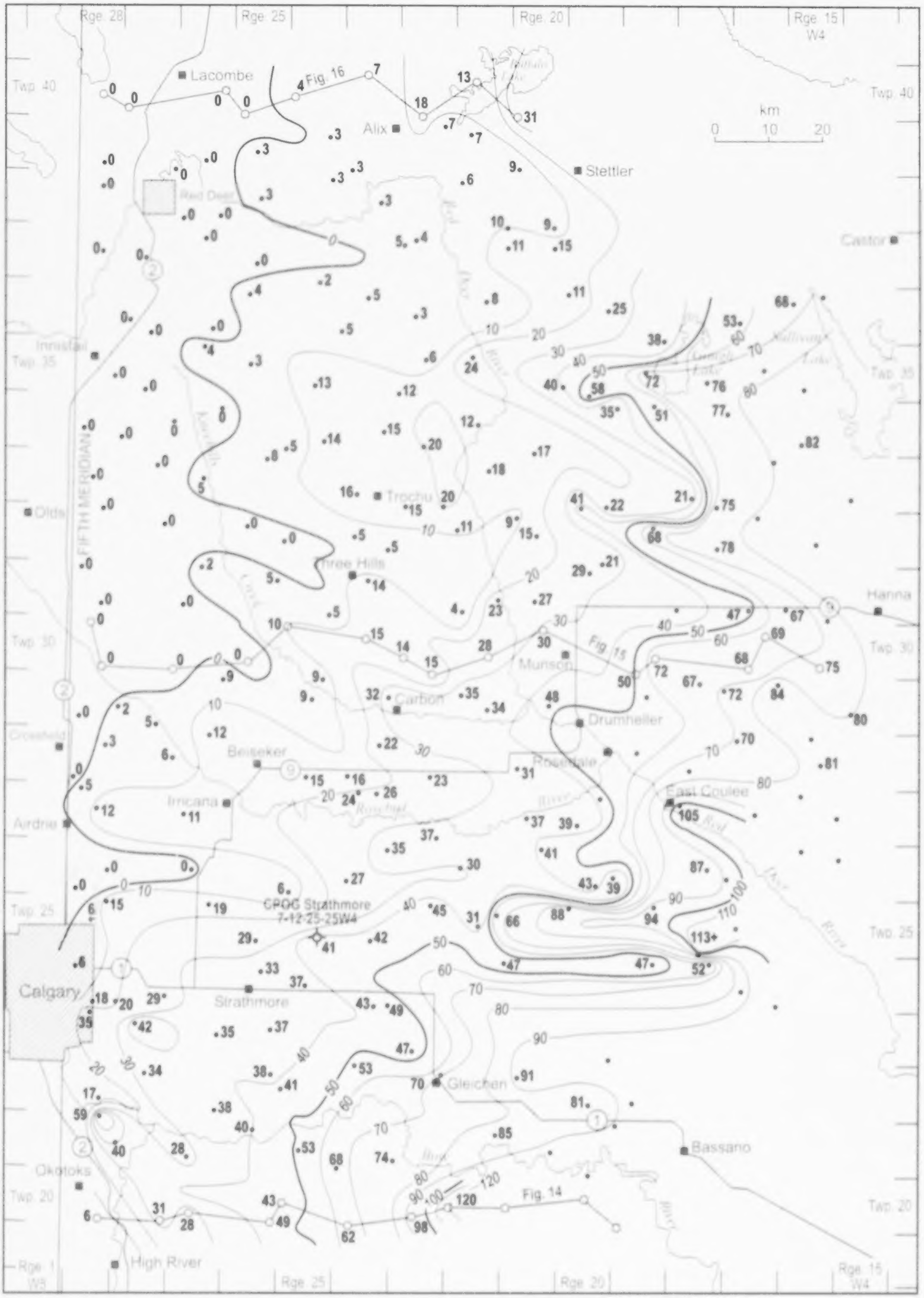


Figure 19. Isopach (in metres) of middle Bearpaw tongue.

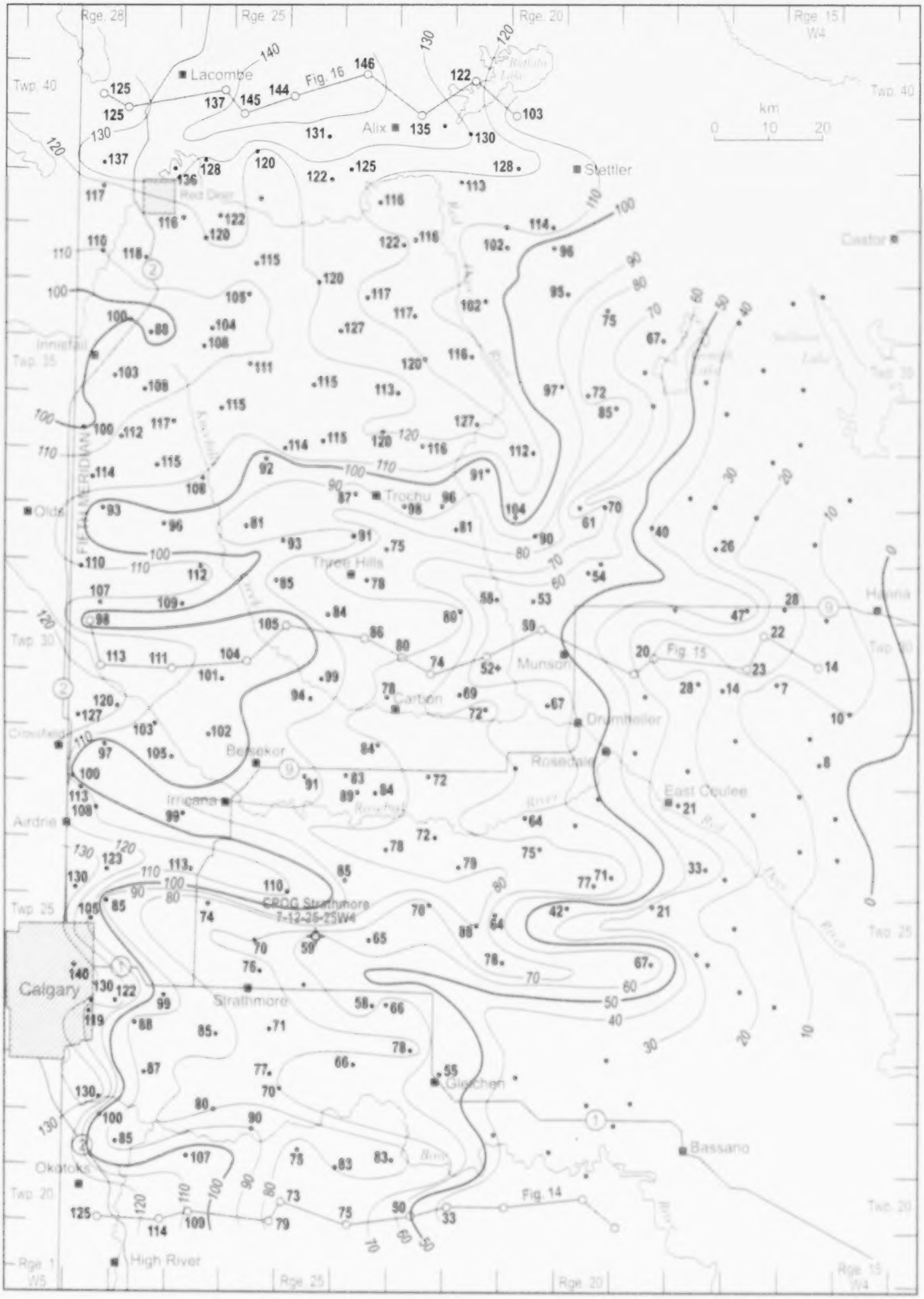


Figure 20. Isopach (in metres) of Hoodoo tongue.

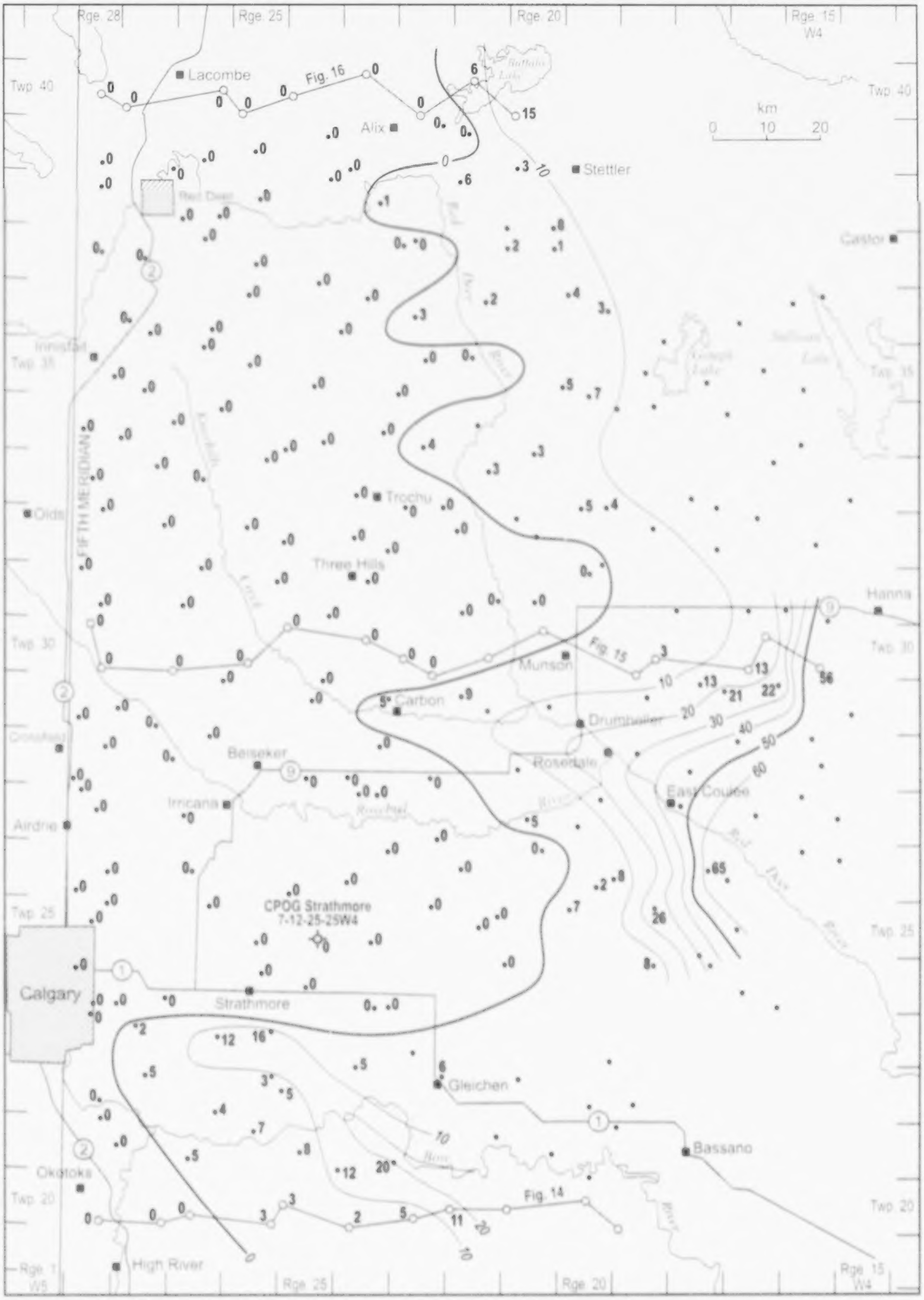


Figure 21. Isopach (in metres) of Upper Bearpaw tongue.

record is lost behind casing. It presumably merges into the main body of Bearpaw marine shale farther eastward. The position of the zero pinchout is 20 to 30 km eastward of that for the middle Bearpaw tongue, again illustrating the southeastward stepping of depositional loci with each successive transgressive-regressive cycle. Thinning toward the northwest occurs from the top, and the zero pinchout crosses the Red Deer River outcrop belt at about the location of Drumheller. The marine influence of this unit is only identified positively in outcrop at the Drumheller South section in this study area, where there is a 1 m cemented sandstone with a sharp top, desiccation cracks, and *Skolithos* burrows at the top Hoodoo-base Midland contact. Distinct trends of thinness correspond roughly to similar trends of thickness in the overlying Midland tongue.

The Midland tongue (Fig. 22) displays similar relations to those expressed by the underlying East Coulee and Hoodoo tongues, but translated geographically to the southeast. Sandy input was derived mainly from the west and northwest, and spread eastward and southeastward to a presumed zero pinchout well beyond the limits of the study area and database. Based on subsurface cross-sections, the thinning takes place from the base of the unit toward the southeast. The unit occurs in outcrop at all sections on the Red Deer River between Drumheller and Bleriot Ferry, and on the Rosebud River between Rosedale and Beynon. This unit includes the bulk of the strata present in the banks of the river in the vicinity of the City of Drumheller and the Royal Tyrrell Museum, and is one of the main coal-bearing portions of the Horseshoe Canyon Formation. Thicknesses are about 130 to 170 m along the Fifth Meridian, and west-east linear trends of 110 to 120 m thickness, interpreted to represent fluvial-dominated valley fills, commonly extend eastward many tens of kilometres. The subsurface database is complete only in the western half of the study area as a result of its shallow position behind casing and erosional removal to the east.

Data on the Drumheller marine tongue (DMT, Fig. 23) is very limited because its areal extent is at the limit of the subsurface data available at that stratigraphic level of the Horseshoe Canyon Formation in this study area. The data currently available does indicate depositional characteristics similar to those of the lower, middle and upper Bearpaw marine tongues. In fact, the DMT is here interpreted as simply another regional-scale Bearpaw marine tongue. It was historically treated as a unique feature in former outcrop studies because the other Bearpaw tongues were not recognized in exposures, and no regional-scale study and correlation of surface and subsurface data had been previously attempted. The northwestward thinning reaches a zero pinchout along a line from Carbon to Strathmore to Okotoks, and thickens toward the southeast before the surface and subsurface record is lost. The unit presumably merges into the main body of Bearpaw Formation marine shale farther eastward, as do each of the lower marine tongues. The position of the zero pinchout is in the same vicinity as that for the upper Bearpaw tongue, although the data is too sketchy to speculate further. Thinning toward the northwest occurs from the top, and the zero pinchout crosses the Red Deer River outcrop belt at about the location of Bleriot Ferry. This unit is only identified positively in outcrop at the Blue Bridge, Mile 70.5, Horseshoe Canyon, and Dunphy Cemetery sections in this study area, where there are thin oyster shell beds at the base of the Tolman tongue. The unit is also known at Horsethief Canyon, across the Red Deer River from Orkney Hill, although this section was not measured for this study. At Bleriot Ferry, there is a thin bed of greenish sandy siltstone with a few scattered oyster shells apparently located within the Tolman tongue, which cannot currently be correlated with any other occurrence, but may indicate the presence of a higher marine tongue, only present southeastward of this location where the relevant stratigraphic level is eroded away. There are no distinct trends of thinness mappable in this meagre data set.

The Tolman tongue (Fig. 24) can only be mapped in subsurface in the western half of the study area. It is present in outcrop between Orkney Hill and Dry Island on the Red Deer River, between Iron Bridge and Rosebud on the Rosebud River, and between Dunphy and Carbon on Kneehills Creek, and as fine exposures in the Horseshoe Canyon area. This unit is very distinctive in that it is the only portion of the Horseshoe Canyon Formation conspicuously devoid of coal and composed primarily of greenish pedogenic siltstone with minor sandstone. Facies present are much more reminiscent of the St. Mary River Formation to the south than they are of the rest of the Horseshoe Canyon Formation. Sediment input was derived mainly from the west, and spread eastward and southeastward to a presumed zero pinchout well beyond the limits of the study area and database. Unlike the other units designated in this study, there is only minor thinning from the 5th meridian (80–100 m thick) toward the east (60–80 m thick), although the data set is inadequate to fully define the trend. West-east linear thickness trends of 80–100 m extend eastward many tens of kilometres, which are interpreted to mark main sediment input points.

The Carbon tongue (Fig. 25) is the uppermost unit in the Horseshoe Canyon Formation and so is only present in subsurface in the western half of the study area. Sediment input was derived mainly from the west, and spread eastward and southeastward to a presumed zero pinchout beyond the limits of the study area and database. There is irregular west-east thinning and thickening (generally in the 50–80 m range) through much of the study area. The Carbon is present in outcrop between Tolman Bridge and Dry Island on the Red Deer River, between Mile 74 and Rosebud on the Rosebud River, and between Appleyard

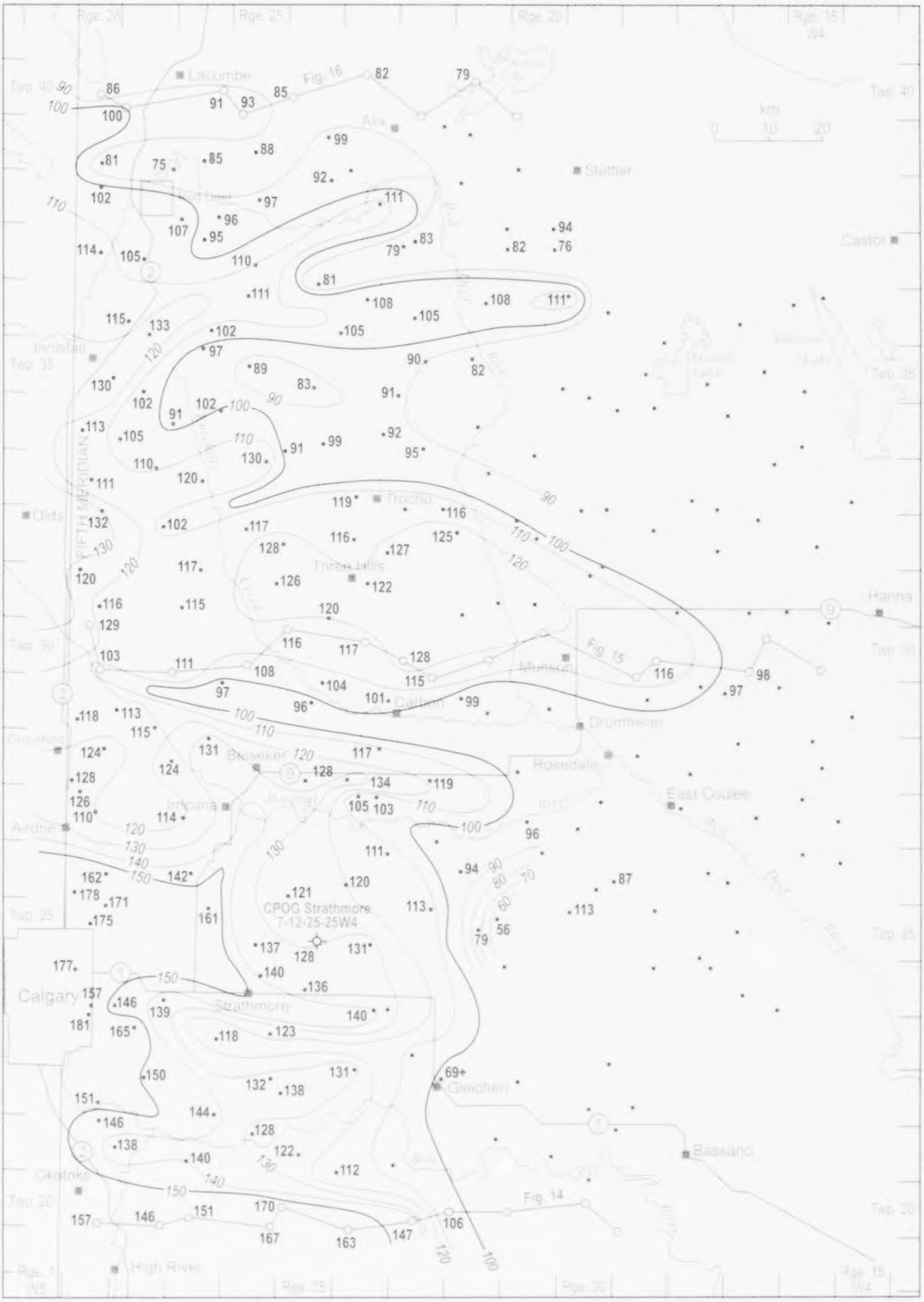


Figure 22. *Isopach (in metres) of Midland tongue.*

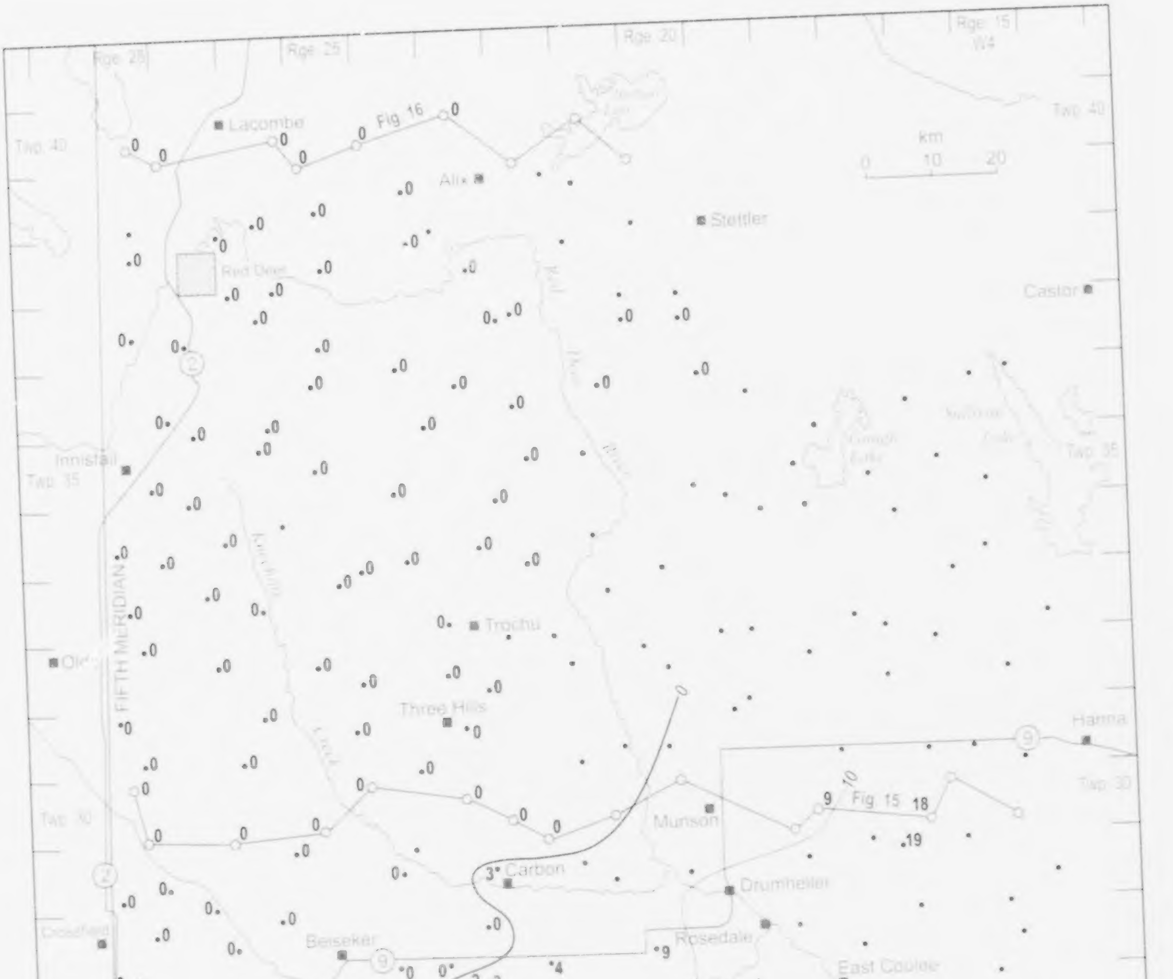


Figure 23. Isopach (in metres) of Drumheller marine tongue.

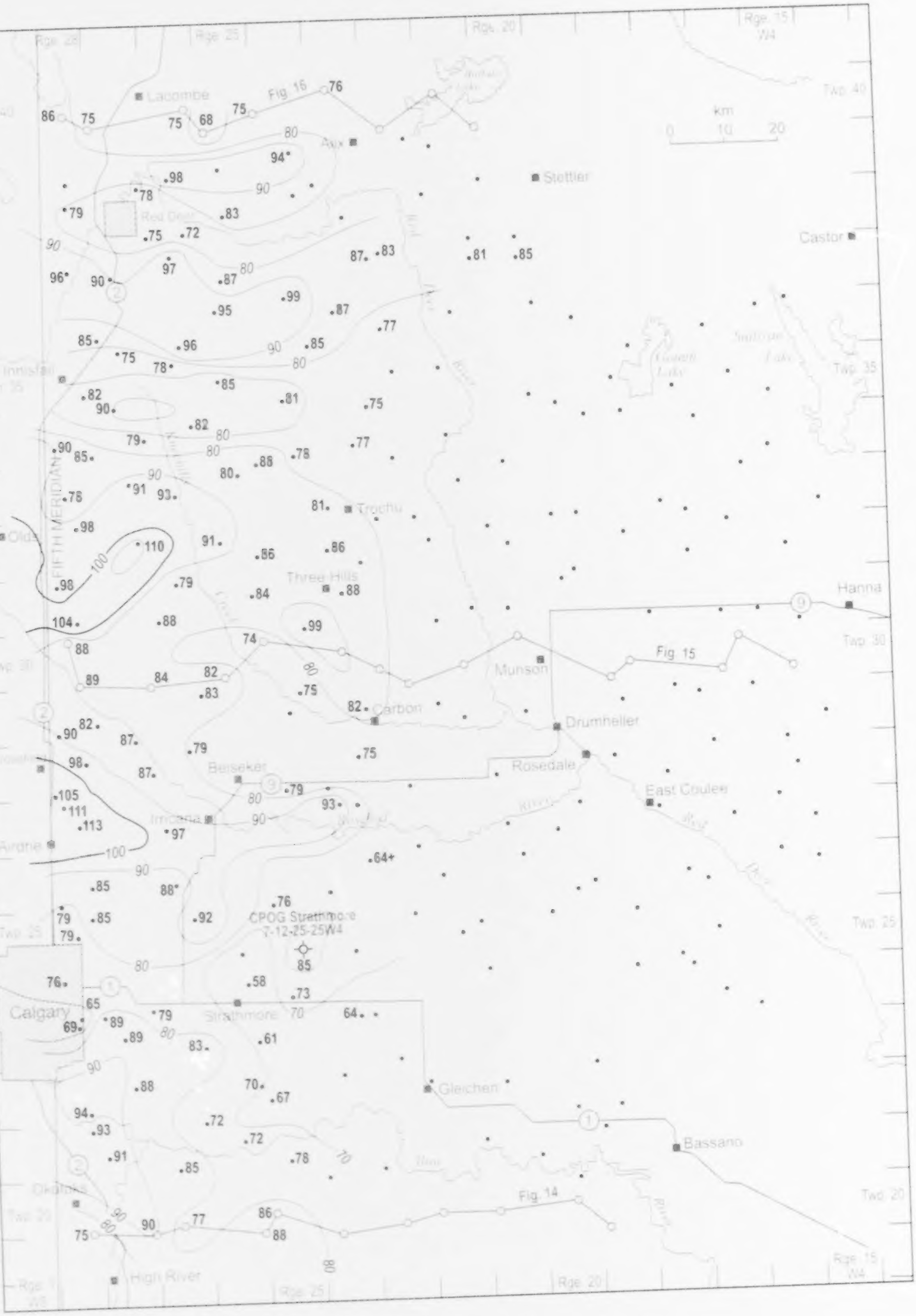


Figure 24. Isopach (in metres) of Tolman tongue.

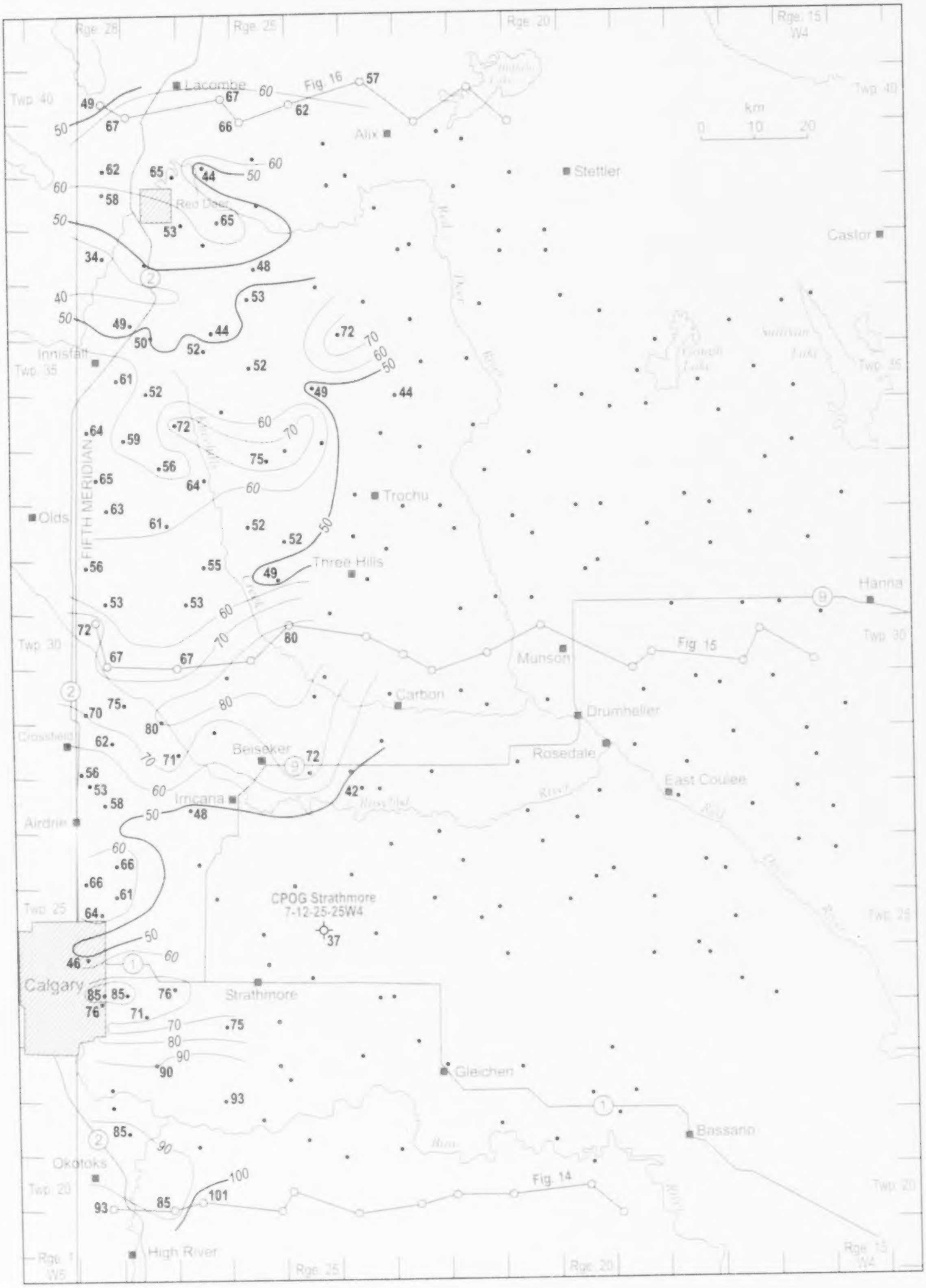


Figure 25. *Isopach (in metres) of Carbon tongue.*

Coulee and Carbon on Kneehills Creek, and as fine exposures in the Horseshoe Canyon area. Several wide, linear, west-east trends of sediment thickness appear to be present, interpreted to represent fluvial-dominated valley fills. However, part of the thickness variation is a result of planation beneath the unconformity-based Battle and Scollard formations, which overlie the Carbon tongue.

SEDIMENTOLOGICAL BACKGROUND

Summary of previous interpretations

Foothills. In the central Foothills (northwest of the study area) Jerzykiewicz (1985) identified three two-part cyclothems of the upper Brazeau Formation of the Saunders Group, totalling 375 m thick in a coarsening-upward succession. These strata together approximate the Edmonton and St. Mary River formations of other areas. Cyclothem IIa (120 m thick) has a prominent 10 m thick, laterally persistent, multistoried channel sandstone at the base and consists of about 34 per cent thin, relatively fine-grained channel sandstone units with intraformational conglomerate lags at their bases. Overbank sediments are dark mudstone with splay and levee siltstone to very fine sandstone beds and a few thin bentonite beds. Cyclothem IIb (20 m thick) is 88 per cent overbank mudstone with coal and minor sandstone. Cyclothem IIIa (75 m thick) is 62 per cent thick, multistorey channel sandstone with horizontal lamination, parting lineation, and lags with tree trunks, passing upward into trough-crossbedded and planar-crossbedded sandstone. Cyclothem IIIb (25 m thick) is 74 per cent overbank mudstone, carbonaceous shale, and coal with minor thin splay sandstones. Cyclothem IVa (75 m thick) is 71 per cent very thick channel sandstone as above with 29 per cent overbank mudstone without bentonite. Finally, cyclothem IVb (50 m thick) has 56 per cent overbank coaly mudstone, and common bentonites (and is possibly equivalent to the Battle-Kneehills Tuff Zone). Future work may suggest relations between these units and the members defined in this report.

In the southern Foothills and southwesternmost Plains, strata approximately equivalent to the Horseshoe Canyon Formation are included in the Blood Reserve and St. Mary River formations. The Blood Reserve Formation (Fox Hills Formation of Sanderson, 1931, and Link and Childerhose, 1931) is a cliff-forming, light grey to buff, uniform, feldspathic, fine- to medium-grained sandstone unit with calcareous to argillaceous cement (Young and Reinson, 1975; Lerand, 1983; Glass, 1990). It overlies a coarsening-upward Bearpaw sequence of dark grey, laminated mudstone and siltstone with marine foraminifera, pelecypods, ammonites and pleisiosaur fossils (Link and Childerhose, 1931; Clark, 1931; Young and Reinson, 1975; Nadon, 1988). The Blood Reserve was deposited on the embayed western shoreline of the Bearpaw sea and prograded basinward as a coarsening-upward, tidally influenced barrier island sequence overlain by minor backbarrier lagoonal coal and oyster beds (Young and Reinson, 1975; Lerand, 1983; Nadon, 1988). Lerand (1983) interpreted the barrier shoreline as oriented northeast-southwest with offshore to the southeast, including tidal inlet channels, whereas Nadon (1988) inferred a more complex northwest-southeast-trending barrier prograding into an east-west seaway embayment. Nadon (1988) described several facies associations as follows:

1. Tidal channel fine- to medium-grained sandstone within the mesotidal barrier complex, erosional bases with lags of wood fragments and intraclasts, trough-crossbedding, wave ripples, unidirectional northeastward flow, *Ophiomorpha* and *Rosselia* burrows near the top.

2. Low-energy prograding shoreline very fine- to fine-grained sandstone, parallel lamination and minor scour surfaces, sharp top with wave ripples and bioturbation.

3. High-energy prograding shoreline and strandplain fine- to medium-grained sandstone, coarsening-upward from marine sediments with *Ophiomorpha* burrows, to tidal crossbedded sandstone with bidirectional flows, to foreshore parallel- and low-angle laminated fine- to medium-grained sandstone with *Macaronichnus* burrows.

The overlying and much thicker St. Mary River Formation represents the accompanying nonmarine clastic wedge, dominated by overbank fines and anastomosed fluvial channels that prograded from the southwest to the northeast (Lerand, 1983; Nadon, 1988; Hamblin, 1998d). This progradation direction is at right angles to that displayed by the Horseshoe Canyon Formation, and implies that the St. Mary River represents a separate clastic wedge in southwestern Alberta, which may interfinger with the Horseshoe Canyon south of the current study area, as suggested by Hamblin (1998a). Further research on this relationship is clearly necessary.

The St. Mary River Formation is generally composed of interbedded siltstone, shale and sandstone, with minor bentonite, coal and freshwater mollusc-rich carbonate deposits (Young and Reinson, 1975; Rahmani and Schmidt, 1975; Hamblin, 1998a, d). The sandstone is greenish, calcareous, fine-grained, and lenticular, interbedded with grey and green friable silty shale (Glass, 1990). The basal portion, up to 30 m thick, is fissile grey shale and siltstone with abundant wood fragments, brackish water coquinas up to 1m thick, and thin coals, interpreted as brackish backbarrier lagoonal sediments (Young and Reinson,1975; Lerand, 1983; Glass, 1990). Minor, broad, shallow, burrowed, and laminated fine-grained sandstone channels with erosional bases and inclined heterolithic stratitification (IHS), or coarsening-upward splay sandstones are present throughout (Jerzykiewicz and Norris, 1994; Hamblin, 1998). The bulk of the unit is nonmarine, interbedded, fine-grained sandstone and siltstone with freshwater molluscs and dinosaur bones (Nadon, 1988; Glass, 1990). Poorly sorted mudflow deposits, interpreted as distal deposits at the periphery of alluvial fans, are present along Highwood River in the middle portion of the St. Mary River Formation (Jerzykiewicz and Norris, 1994). Unlike most of the Horseshoe Canyon Group, coal is uncommon; lithofacies are most similar to those of the Tolman tongue as described in this study. The following facies associations were described by Nadon (1988):

1. Fluvial channel fine- to medium-grained sandstone in meandering point bar sheets up to 4.5 m thick with IHS and clay plugs, or as multistoried, erosionally based fining-upward lenses (width:depth = 8–25:1) with trough crossbedding but no IHS or clay plugs and interpreted as anastomosing fluvial. Rahmani and Schmidt (1975) described classical fining-upward fluvial cyclothems up to 7 m thick.

2. Proximal splay channel fine- to medium-grained sandstone in sharp-based lenses 2 m thick by 5 m wide, encased in mudstone.

3. Crevasse splay calcareous siltstone to medium-grained sandstone in thin, very extensive sheets with parallel lamination, climbing ripples, wave ripples and roots.

4. Overbank dark to light grey laminated and rooted siltstone, lacustrine burrowed limestone with shells and greenish paleosol siltstone with slickensides and nodular ironstone caliche limestone.

Plains. In central Alberta, Edmonton Group strata, first described by Tyrrell (1887), represent a variable sequence of complexly interfingering, fresh to brackish water sandstone, siltstone, sandy mudstone, coal, and ironstone concretions, which grades westward into the upper Brazeau Formation (Irish, 1970; Yurko, 1975; Gibson, 1977; Glass, 1990; Hamblin, 1998b). The depositional setting is generally fluviodeltaic (Yurko, 1975) and the relatively thin sandstone deposits represent shoreline and fluvial channels, whereas mudstones represent overbank floodplain environments (Williams and Dyer, 1930). One thin, but significant, marine tongue was described in outcrop in the middle of the formation. In addition, there is less coal and more lacustrine shale to the west (Williams and Dyer, 1930). All sediments are very bentonitic, usually calcareous, and uniformly fine grained; no conglomerate or coarse sandstone is present (Srivastava, 1968; Allan and Sanderson, 1945). It was divided by Irish (1970), in ascending order, into the Horseshoe Canyon, Whitemud, and Battle formations as discussed above.

The Horseshoe Canyon Formation is generally characterized by a variable sequence of interbedded nonmarine greenish to greyish, sandstone, siltstone and shale with numerous coal and bentonite beds, plus ironstone concretions, deposited in a fluviodeltaic setting (Irish, 1970; Havard, 1971; Gibson, 1977; Shepheard, 1978). Bedding is typically lenticular, with rapid lateral facies changes and discontinuous interfingering beds, so that two measured sections are never the same (Irish, 1970; Shepheard, 1978). The basal portion represents a marine-nonmarine transition from the Bearpaw, followed by predominantly fluvial sediments, then the marine to brackish DMT (in outcrop at Red Deer River), followed by fluvial and lacustrine sediments, and more fluvial deposits beneath the Whitemud Formation. The formation generally thins to the southeast from the base (Ower, 1960), and includes Members A, B, C of Ower (1960) and the Lower and Middle Edmonton of Allan and Sanderson (1945). Sandstone beds are soft, light grey to greenish grey, feldspathic and bentonitic, poorly sorted and argillaceous, very fine to medium grained (never coarse grained) (Allan and Sanderson, 1945; Irish, 1970). They occur in fining-upward lenticular beds with abundant trough crossbedding, planar tabular crossbedding, oscillation ripples, mudcracks and a few burrows (Allan and Sanderson, 1945; Irish, 1970; Gibson, 1977). Mudstone is grey-green or brown, argillaceous and bentonitic, and carbonaceous (Gibson, 1977). Mudstone deposits usually contain abundant wood fragments, bentonite beds, thin coaly streaks, ironstone concretions, beds with plant and dinosaur fossils, and minor oyster beds near the base and in the DMT (Irish, 1970; Gibson, 1977).

The Bearpaw-Horseshoe Canyon transition (lower ~60 m of the Edmonton Group) has been extensively studied in outcrop in the Red Deer River and Willow Creek areas. It encompasses a shallow-marine to shoreline and continental coastal plain transition interpreted as representing rapid deposition in low-energy, unstable environments of an embayed, tidally influenced barrier island-estuarine shoreline oriented northeast-southwest with the offshore direction to the southeast (Shepheard and Hills, 1970; Irish, 1970; Shepheard, 1978; Rahmani, 1983, 1988), a configuration confirmed by this study. The following is a summary of the facies associations, depositional environments and transgressive-regressive history, in ascending order, from the very detailed studies of Shepheard and Hills (1970) and Rahmani (1983):

1. Coarsening-upward delta-front interbedded sandstone and siltstone, and erosionally based tidal channel sandstone, and tidal flat mudstone.

2. Basal transgression, coarsening-upward barrier island sandstone trending northeast-southwest, backbarrier sandstone or mud-filled tidal channels trending northwest-southeast, swamp coal.

3. Backbarrier brackish lagoonal mudstone with thin coarsening-upward sandstone shoals, swamp coal, wide and deep mud-filled and sandstone-filled channels trending north-south.

4. Mesotidal barrier island coarsening-upward sandstone, erosionally based tidal channels trending northwest-southeast, backbarrier mudstone, coal, and coarsening-upward splay sandstone with lenses of glauconitic oyster-filled sandstone.

5. Basal transgression, erosionally based meandering fluvial channel sandstone trending east-west, coarsening-upward splay sandstone, nonmarine overbank mudstone and bentonite, swamp coal.

More recent studies (Saunders, 1989; Ainsworth, 1994; Lavigne, 1999) have attempted to place this same ~ 60 m interval (all contained within the Hoodoo tongue as defined in this report) into a more modern, high-resolution, sequence stratigraphic context. Saunders (1989) studied the paleoseaward zone characterized by Bearpaw open-marine facies and divided the package into three, distinct, transgressive-regressive sequences. Ainsworth (1994) defined seven transgressive-regressive allomembers arranged in an overall seaward-stepping (southeastward) regressive system, all within the Hoodoo tongue, as defined in this study. The allomembers were defined by marine flooding surfaces occurring above coal seams; thus the bases of the seams represent the "turn-around points" from regressive to transgressive conditions. This same concept, at a lower-order more regional scale, is used in this study to define the tongues and fourth-order cycles. The regressional-progradational shoreline packages with sharp-based shorefaces were the result of forced regressions. Subsequent transgressive deposits filled fluvial incisions and induced coal deposition in the back-barrier setting. Maximum regression in that part of the section occurred where one shoreface prograded 21 km toward the southeast (Ainsworth, 1994). Ainsworth (1994) suggested that the fluvial channels were part of a larger incised valley system deposited during transgression on a regional unconformity surface. Lavigne (1999, 2001) argued that the channel units are part of a prograding, tidally influenced deltaic distributary system with decreasing marine influence toward the north, rather than a transgressive tract filling incised valleys and marking a sequence boundary.

The rest of the thick lower Horseshoe Canyon Formation is dominated by nonmarine grey shale and channel sandstone with abundant, laterally continuous coal zones and bentonites deposited on a rapidly prograding, low-topography coastal plain with (?)braided distributary channels and vast overbank areas (Gibson, 1977; Ower, 1960). Large-scale crossbedding and most of the Edmonton dinosaur fossils are typical of this portion of the formation (Allan and Sanderson, 1945). About 185 m from the base in the Red Deer River valley is the Drumheller marine tongue (DMT), a thin but extensive zone reflecting marine to brackish depositional conditions and including one to several hard, thin, lenticular beds of fossiliferous arenaceous limestone, containing pelecypod shells, separated by bluish grey calcareous siltstone (Allan and Sanderson, 1945; Ower, 1960; Srivastava, 1968; Gibson, 1977). It pinches out to the north (north of Twp. 32) and west and was not recognized in the subsurface of Twp. 25, Rge. 25W4 by Ower (1960) or Havard (1971) but, as illustrated in this study, clearly represents the distal portion of an extensive Bearpaw marine tongue from the southeast and thus an event of regional significance. Hamblin (1998c) noted vertical burrows in a thin, fine-grained sandstone bed at the base of the greenish siltstone-dominated unit (Tolman tongue) in the core of 7-12-25-25W4, in the expected position of the DMT.

Immediately above the DMT is a distinctive, thick unit of greenish mudstone with no coal, typically 35 to 60 m thick in outcrop. This is the informally-defined "Tolman member" of Srivastava (1968) or the "fine-grained unit" of Nurkowski and Rahmani (1984), and was also noted by Gibson (1977). It comprises pale green, calcareous, argillaceous to sandy siltstone with minor, sharp-based, fining-upward rippled, very fine- to fine-grained sandstone, arranged in coarsening-upward sequences between laterally extensive, thin bentonite beds (Nurkowski and Rahmani, 1984). Plant fragments, freshwater fern spores and burrows are abundant, but there is no coal, and these sediments were interpreted as lacustrine by Nurkowski (1980) and Nurkowski and Rahmani (1984). The unit generally occurs between coal seams #10 and 11 (Gibson, 1977).

Between this mudstone and the Whitemud sandstone is the "coal-bearing unit" of Nurkowski and Rahmani (1984), or Member C of Ower (1960), or "coaly member" of Srivastava (1968), characterized by thick channel sandstone trending northwest-southeast, thin grey shale, bentonite and the Carbon and Thompson (#11, 12) coal zones, also trending northwest-southeast. This unit has an overall coarsening-upward, more fluvial-upward trend (Nurkowski, 1980). Nurkowski and Rahmani (1984) defined a lower silty and non-coaly member deposited in sinuous mixed-load channels, a middle very coaly member, the coal probably due to a dominance of high-sinuosity suspended load channels, and an upper member dominated by very linear, thick, sandstone trends deposited in less sinuous, bed-load-dominated fluvial channels attributable to an increase in channel gradient (?tectonic influence). The DMT to "fine-grained unit" to "coal-bearing unit" succession was interpreted as being the result of southeastward progradation of a marine-lacustrine-fluvial system of a broad, low-lying, meandering coastal plain on a Bearpaw shoreline by Nurkowski (1980) and Nurkowski and Rahmani (1984).

The previously-defined Whitemud Formation comprises distinctive white-weathering, light grey, kaolinite- and montmorillonite-rich sandstone with lesser siltstone and shale deposited in a fluvial setting on an extensive floodplain (Furnival, 1950; Campbell, 1962; Irish and Havard, 1968; Irish, 1970; Yurko, 1976; Gibson, 1977). The sandstone is fine to medium grained, arkosic, fining-upward, bentonitic and massive with trough and planar-tabular crossbeds and minor pebble lenses (Furnival, 1950; Campbell, 1962; Irish, 1970; Binda and Lerbekmo, 1973; Gibson, 1977; Lerbekmo, 1985). Subordinate mudstone is green or grey, sandy, bentonitic and kaolinitic, with plant fragments, vertical burrows, parallel lamination and ripple crosslamination (Gibson, 1977; Lerbekmo, 1985). Three zones have been identified in Cypress Hills: 1) lower fining-upward, erosionally based, crossbedded sandstone, with paleoflow to the north, east, and south; 2) thin, brown to black, fissile, carbonaceous shale with thin lignite seams, thin lenticular sandstone beds, a freshwater macroflora and deep tap roots; and 3) upper thinly interbedded grey and mauve claystone with tap roots, which appears to represent interfingering with the overlying Battle Formation (Furnival, 1950; Campbell, 1962; Lerbekmo, 1985; Glass, 1990). These members are not distinctive in central Alberta (Glass, 1990). To the southeast in Saskatchewan, the Whitemud is represented only by thin, white, kaolinitic clay (Caldwell, 1968). Deposition occurred in slow-moving, low-energy channels on an extensive floodplain far from the sediment source, and the increase in volcanic detritus and decrease in sediment supply suggests subsidence was dominant (Binda and Lerbekmo, 1973; Gibson, 1977). The kaolinite-rich sediments are the product of intense chemical diagenesis and in situ kaolinitization (Furnival, 1950; Lerbekmo, 1985).

The overlying Battle Formation (or Blackmud member of Srivastava, 1968) is one of the most distinctive units in the stratigraphic package and comprises purple to mauve weathering, greenish grey to dark brown to black, thin bedded, bentonitic silty mudstone with scattered sand grains and abundant organic matter (Srivastava, 1968; Irish, 1970; Gibson, 1977; Glass, 1990). One to several distinctive hard, silicified, pale grey tuff beds occur near the top (Irish and Havard, 1968; Irish, 1970; Gibson, 1977). This thin, areally extensive unit was previously considered the upper member of the Whitemud (Furnival, 1950). The Battle Formation is predominantly decomposed ash and has no diagnostic fossils, but contains some mudcracks and a continental microflora and algae (Irish and Havard, 1968; Binda and Lerbekmo, 1973; Glass, 1990). In Cypress Hills, Furnival (1950) defined a lower, dark, bentonitic shale member conformable with the Whitemud, and an upper member of thinly interbedded greenish sandstone, siltstone and shale with bentonite, and an erosional top. The Battle Formation is highly siliceous and montmorillonitic, representing a volcanic maxim, but shows no evidence of extensive kaolinitization like the Whitemud (Furnival, 1950). It was interpreted to represent very slow aggradation of airborne ash in extensive, calm, shallow lakes and swamps on a floodplain, as a result of a marked rise in water table (Irish and Havard, 1968; Binda and Lerbekmo, 1973; Lerbekmo, 1985).

The Kneehills Tuff(s) in the upper part of the Battle Formation comprises pale grey, hard, massive, uniform, siliceous and bentonitic claystone with opal- and chalcedony-filled vugs (Allan and Sanderson, 1945; Srivastava, 1968; Ritchie, 1960; Irish, 1970; Glass, 1990). There are fresh angular quartz and feldspar fragments, with some rounded zircon grains and some parallel lamination suggesting that the ash was windblown and deposited in fresh water with some detrital material (Allan and Sanderson, 1945; Ritchie, 1960; Gibson, 1977; Lerbekmo, 1985). The Tuff may be represented by several thin beds. It is nearly continuous over much of Alberta and is a very good time-stratigraphic marker (Allan and Sanderson, 1945; Ritchie, 1960; Irish, 1970; Lerbekmo, 1985). It is possible that major ashfalls occurred with a frequency of hundreds to thousands of years but were preserved only as individual beds in coal swamp and lake environments as in the Battle (Lerbekmo, 1985). The various published radiogenic ages of the Kneehills Tuff centre about 66 to 67 Ma (see previous discussion).

Cypress Hills. In Cypress Hills, far to the southeast and separated from the present study area by 250 km of nonpreservation, the Horseshoe Canyon-equivalent is the Eastend Formation, the marine to nonmarine shoreline unit transitional from the underlying Bearpaw. It correlates approximately with the upper Horseshoe Canyon Formation and is overlain by the Whitemud and Battle formations (Russell and Landes, 1940; Furnival, 1950; Caldwell, 1968). The Eastend Formation generally comprises yellow to buff to grey sandstone and coarse siltstone with a sparse marine molluscan fauna near the base and minor lignite or carbonaceous shale near the top (Russell and Landes, 1940; Furnival, 1950; Glass, 1990). Sandstone is fine- to medium-grained, coarsening-upward, silty, feldspathic, and limonitic, with concretions, lenticular bedding, and crossbeds (Russell and Landes, 1940; Furnival, 1950; Caldwell, 1968; Glass, 1990). Thin beds of grey to dark green siltstone are present, especially near the top (Furnival, 1950). Russell and Landes (1940) described a typical upward sequence of thick, crossbedded sandstone, to thinly interbedded sandstone and siltstone, to massive sandstone, to thinly interbedded sandstone, mudstone and lignite, to buff-coloured siltstone. The Eastend Formation generally becomes finer grained and dominated by siltstone to the east in southern Saskatchewan (Caldwell, 1968).

Petrography

In the central and southern Foothills Mack and Jerzykiewicz (1989) identified Petrographic Stage II of the post-Wapiabi succession as representing the upper Brazeau-St. Mary River sequence. Compared to underlying strata it is characterized by an increase in metamorphic rock fragments and a decrease in carbonate and chert sedimentary rock fragments. This was interpreted by those authors to represent a decline in the influence of the nearby Rockies Thrust Belt sediment source and an increase in the influence of the Omineca Belt sediment source farther to the west, plus significant volcanism. In the central Foothills, the upper Brazeau contains plagioclase plus volcanics (56–76%), polyquartz plus metamorphics (10–20%), and monoquartz plus sedimentary (13–21%), indicating major dominance of a volcanic sediment source, possibly to the west in the now-eroded roof rocks of the Omineca Belt (Mack and Jerzykiewicz, 1989). In the southern Foothills, the St. Mary River Formation contains plagioclase and volcanics (30%), polyquartz plus metamorphics (25%), and monoquartz plus sedimentary (45%), suggesting more balance between input from the Omineca and the Rockies belts (Mack and Jerzykiewicz, 1989). The Blood Reserve Formation is characterized by very quartzose, medium-grained sandstone with calcareous or argillaceous cement (Russell and Landes, 1940; Lerand, 1983; Glass, 1990). The overlying St. Mary River Formation has very calcareous, fine- to medium-grained sandstone and silty shale (Russell and Landes, 1940; Glass, 1990).

In the Plains the Edmonton Group is generally composed of calcareous, argillaceous fine-grained sandstone, with little coarse-grained material, and siltstone (Allan and Sanderson, 1945). The sandstone display fair to poor sorting, and is arkosic, with 40 to 65 per cent of fresh to angular grains of plagioclase, plus angular quartz and minor biotite and muscovite (and a few heavy minerals) set in a bentonitic matrix comprising up to 35 per cent of the rock (Allan and Sanderson, 1945). Rahmani and Lerbekmo (1975) identified two heavy mineral provinces: zircon-apatite in the south, west, and southeast, and garnet-apatite-sphene in the northeast. They related these to northwest-to-southeast transport from a positive source area in northern and central British Columbia. These authors also noted that the Edmonton Formation has a distinct lack of hornblende, epidote, clinozoisite and plutonics and low metamorphic content, but is dominated by volcanic and sedimentary detritus, again through input from the Omineca and Rockies belts. The lithic sandstone in the Horseshoe Canyon Formation is typically very fine to medium grained, graded, argillaceous and feldspathic, and dominated by sedimentary rock fragments, quartz, chert, plagioclase and K-feldspar, with cements of montmorillonite, kaolinite, illite and calcite (Irish, 1970; Gibson, 1977). There is a striking bimodality of grain size (sandstone vs. clay) but some of the argillaceous material results from diagenesis and, in fact, secondary calcite replaces much of the clay and shale rock fragments (Shepheard and Hills, 1970). In southeastern Alberta the equivalent Eastend Formation comprises fine- to medium-grained, feldspathic, argillaceous sandstone dominated by volcanic lithic fragments (Furnival, 1950; Glass, 1990).

Overlying the Horseshoe Canyon Formation, the Whitemud and Battle formations, or Kneehills Tuff Zone, have received some attention because of their unusual lithologies. The very fine- to coarse-grained (generally fine to medium) sandstone of the Whitemud is feldspathic, arkosic, kaolinitic and bentonitic (Glass, 1990; Gibson, 1977). Grains are subround to subangular, with mono-and polyquartz (25–60%), feldspars (5–20%), and rock fragments (30–60%). Fines range from 4 to 43 per cent, and average 22 per cent, and are mostly montmorillonite and kaolinite (Binda and Lerbekmo, 1973; Gibson, 1977). The kaolinite is derived from intense in situ chemical diagenesis of the feldspar-rich sediments (Binda and Lerbekmo, 1973; Lerbekmo, 1985). The Battle Formation dark, bentonitic mudstone contains mostly montmorillonite (decomposed volcanic ash; Irish and Havard, 1968), with minor kaolinite, illite, chlorite and abundant organic matter (Gibson, 1977; Lerbekmo, 1985). Up to 10 per cent of the rock is made up of sandstone and siltstone grains of quartz, feldspar, chert and euhedral zircon with accessory heavy minerals (Gibson, 1977; Glass, 1990). Within the Battle, commonly near the top, are one to several ashfall beds, known as the Kneehills Tuff (Ritchie, 1960). It is composed mainly of angular fresh quartz, feldspar and glassy volcanic shards set in an isotropic groundmass of opaline silica and montmorillonitic clay (Ritchie, 1960; Gibson, 1977; Nurkowski, 1980). The overall composition is greater than 90 per cent silica, partly as a result of secondary chalcedony and opal emplacement (Allan and Sanderson, 1945; Ritchie, 1960).

Paleopedogenetic deposits

General. Paleosols are important components of the Horseshoe Canyon Formation, particularly in its middle and upper parts. Although these have been mentioned in several reports, little description or interpretation of these deposits has been published. Recognition and interpretation of paleosols can assist in the interpretation of significant stratigraphic surfaces, subaerial depositional and erosional processes, and paleoclimatic setting (Barclay, 2000). Therefore I will review here the basics of the paleopedogenetic motif that bears on these strata.

A paleosol is a body of mineral and organic matter that was altered in situ in response to variations of physical and chemical weathering and biogenic action when it was in the weathering zone near the surface (Retallack, 1981; Buol et al., 1989, INQUA, 1990). Soil formation is a normal and continuous process in terrestrial settings: most floodplain deposits, where the sedimentation rate is only a few millimetres per year, allowing a long residence time of tens to thousands of years, have been extensively pedogenically modified. (Allen and Wright, 1989).

Controls and processes. Soil formation proceeds through discrete stages bounded by definite threshold states (Robinson et al., 2000). Firstly, pedoturbation destroys the original layering of the parent material, especially near the top of the weathering profile. Destratification develops within a few hundred to a few thousand years, through the direct action of plant roots or infauna, mixing by shrinkage and swelling of expandable clays, and freeze and thaw expansion and contraction (Allen and Wright, 1989). The common effects of wet and dry alternations lead to a dominance of vertical structures of elongate columnar and prismatic forms ("peds"). Over time the removal of matter from one horizon ("eluviation") and concentration of that matter into a lower horizon ("illuviation") begins to dominate pedogenesis (Allen and Wright, 1989; INQUA, 1990). This downward translocation of clays to form a distinctive B Horizon may take thousands of years to complete and represents prolonged exposure. Prominent concentrations of iron- and/or carbonate-rich beds are called "duricrusts". Examples of peds, eluvial and illuvial horizons, and duricrusts are present in Horseshoe Canyon strata.

Floodplain aggradation moves the soil from the oxidizing weathering zone downward into the waterlogged phreatic zone, causing a loss of primary colouration by iron reduction, and the formation of drab haloes or reduction spots (Allen and Wright, 1989). The natural episodic nature of sedimentation processes on a floodplain suggests that unconformities and sedimentological hiatuses are ubiquitous and may mark times of profound pedogenesis (Retallack, 1981). The degree of pedogenetic modification depends on the residence time of the parent material in the zone of soil formation, and on the rate of pedogenesis (depending on local sedimentation rate) (Allen and Wright, 1989). In areas of greater relative subsidence, reduced drab soils and thick peats can accumulate (as in the Horseshoe Canyon Formation), whereas in areas that are stable or rising, leached soils and minor peat are more likely (Allen and Wright, 1989). Thick profiles are favoured if slow rates of deposition and erosion are maintained for long periods; rapid changes limit pedogenesis.

The rate of pedogenesis is affected by intensity of weathering (greater in shallow soils), retrogression (reversals of soil-forming processes such as wet/dry cycles) and pedological inertia (resistance to further change, once begun) (Buol et al., 1989). The rate of full soil profile formation ranges from 45 years (1.3 a/cm) for a weakly-developed soil, to 75 000 years (750 a/cm) for a thick, well-developed soil (Leeder, 1976; Buol et al., 1989). Visible carbonate accumulations can arise in as little as 100 years, and well-developed profiles in a few thousand years (Leeder, 1976; Allen, 1986). Maturation may be terminated at any time by external factors, hence many preserved paleosols are immature.

Recognition. Retallack (1988) suggested that three main features of paleosols are most diagnostic in field observations: a) root traces (irregular, downward tapering and branching, may be truncated by an erosion surface at the top), b) soil horizons (gradational lower boundaries parallel to truncated upper surface), and c) soil structures (massive, hackly, jointed, with well-defined peds, and concretions or nodules) (Fig. 26).

Root traces are clear evidence of subaerial exposure and plant colonization: shallow, spreading root systems are preserved in waterlogged lowland settings, whereas lack of definable structures or deeply penetrating rhizocretions are more typical of seasonally wetted or better drained areas (Retallack, 1988). The fossil remains or traces of terrestrial gastropods, vertebrates or arthropods may also be present.

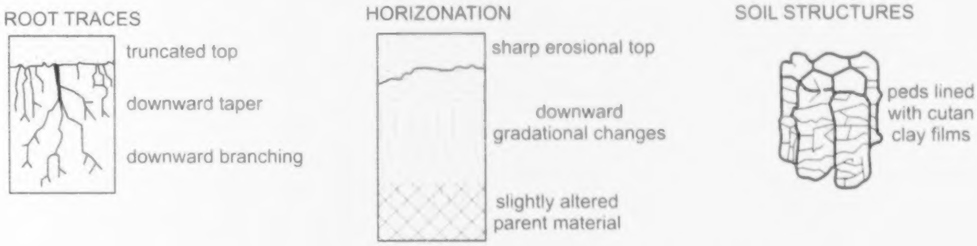


Figure 26. *Diagnostic paleosol features (modified from Retallack, 1992).*

Prominent light grey to white colours ("ganister" or silicified quartz sandstone) commonly represent strong acidic leaching of mineral and organic components ("eluviation") typical of successions with numerous coal seams (Allen and Wright, 1989). In reducing settings, soils tend to contain reduced iron and so are dark and drab in colour ("gley"). Colour mottling, a result of localized changes in oxidation and reduction, develops rapidly and is also common. Soils that develop in a mostly waterlogged climate that occasionally dries out have a groundmass of reduced dark soil with local zones of oxidation ("gley mottling") (Allen and Wright, 1989).

Pedoturbation, or destratification, processes destroy the original layering of the parent material (Allen and Wright, 1989) within a few hundreds to a few thousand years, and the resulting hackly, massive to blocky jointed texture of pedogenic sediment is distinctive (Retallack, 1981; Van Houten, 1982; Retallack, 1988). In materials with abundant montmorillonitic or smectitic clays (common in Horseshoe Canyon deposits), repeated wetting and drying typically creates vertically oriented structures that crosscut the original layering and contribute greatly to mixing (Allen and Wright, 1989). Elongate columnar and prismatic aggregates, called peds, result from repeated opening and closing of an array of desiccation cracks. The peds are defined by an irregular network of planes, called cutans, lined by thin skins of clay or minerals marked by randomly oriented slickensides (Retallack, 1988). Definable peds, cutans and slickensides are typical of periods of intense pedogenesis in seasonally wetted soils rather than constantly waterlogged areas (Retallack, 1988). Crusted, nodular or concretionary concentrations ("glaebules") of carbonate, iron and silica are very common in certain soil profiles (Van Houten, 1982) and appear as sharply defined, irregular lumps, mineralogically different from the enclosing sediment. The upper boundaries of paleosols tend to be quite sharp, but most of the horizon boundaries are diffuse and highly irregular, particularly at the base (Van Houten, 1982; Retallack, 1988).

Paleosol classification. Mack et al. (1993) proposed a classification system, primarily for ancient soils, which relies on "geological" properties likely to be preserved over time (Fig. 27). The main attributes of the five orders of paleosol that have importance in the Horseshoe Canyon Formation follow.

Paleosols whose most prominent characteristic is lack of horizonation due to homogenization by pedoturbation and shrink/swell dynamics of abundant expandable clays are called "vertisols". These are characterized by rapid development of dark colours, homogenization and dominantly vertic features such as deep desiccation cracks and wedge-shaped peds (Duchafour, 1982). They develop on parent materials with abundant expandable clays due to alternating seasonal wet/dry phases (Duchafour, 1982; Buol et al., 1989; Allen and Wright, 1989). Only the presence of a distinct drying season is important, not the length of that period, and they are much more common in relatively low slope, poorly drained areas (Duchafour, 1982; Buol et al., 1989). During the dry season, deep desiccation cracks form and can partially fill with mixed surface debris, but upon wetting the clays expand, creating peds that slide against each other, developing cutans with slickensides (Buol et al., 1989). Desiccation cracks, wedge-shaped peds, slickensides and clastic dykes are all common.

Paleosols with grey-green colours, organics, and pyrite, develop in the waterlogged reduction zone of a high water table setting and are called "gleysols". In areas of fluctuating water table, irregular diffuse patches of gley colour mottling and nodules or concretions of iron or

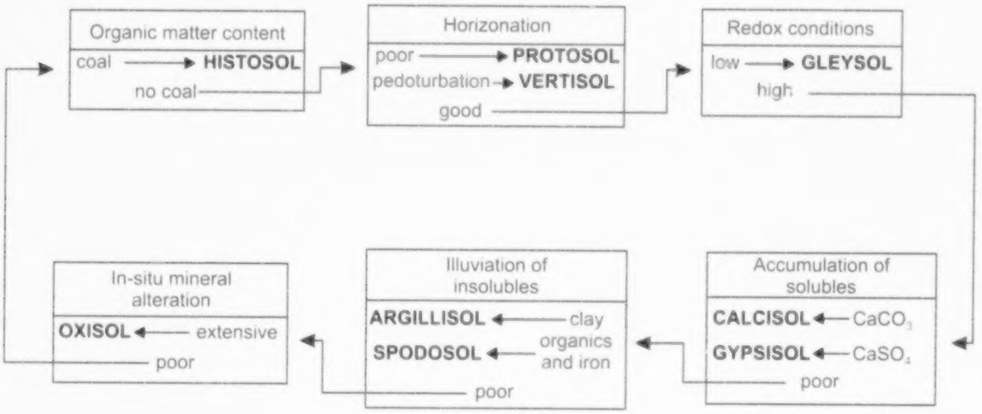


Figure 27. *Simplified flow chart for classifying paleosol orders, using the most prominent pedogenic features (from Mack et al., 1993).*

manganese are typical. They are characteristic of poorly drained areas with high water tables, like lower delta plains (Duchafour, 1982), have weak horizonation due to the lack of vertical translocations in waterlogged soils, and are commonly capped by a coal. They generally have grey drab colours (reduced iron), rootlets, mottling and abundant sideritic concretions in the lower zones precipitated from freshwater (Allen and Wright, 1989). Vertisols and gleysols are common components of the siltstone facies of most parts of the Horseshoe Canyon Formation.

Paleosols characterized by significant accumulations of soluble carbonate as discrete horizons are referred to as "calcisols". These may occur as discontinuous veins and coatings, scattered nodules or tubules, or massive or nodular beds. Commonly, only the lower part of the original profile is preserved (Esteban and Klappa, 1983). Calcisols are typically micritic carbonate, with massive or nodular and peloidal textures, common shrinkage cracks, and dissolution features (Allen and Wright, 1989). Many are pale-coloured and reside in reddened deposits, suggesting arid paleoclimates. However, Kraus (1999) stated that the presence of grey-green soil colours, preserved organic matter, and siderite suggests that the paleosols formed under poorly drained conditions. McCarthy and Plint (1998) pointed out that sideritic bog-ore is characteristic of wetland soils formed in reducing conditions. Sideritic calcisol horizons are present in the Hoodoo, Midland and Carbon tongues, whereas sideritic and calcitic calcisols are particularly common in the Tolman tongue.

Paleosols with a distinct illuvial horizon of accumulated clays, oxides, organics and iron are called "spodosols". The down-profile increase in these materials leaves a distinct clay-organic-iron-poor, commonly white, "albic" horizon at the top. These leached paleosols (called "ganister" when developed on sandy substrates) are usually quartz- and kaolinite-rich, but lack iron, aluminum and other clays (Percival, 1986; Buol et al., 1989). They represent the destratified leached albic eluvial horizon, commonly present beneath coals, and are underlain by the "spodic" horizon where the leached materials were redeposited. They result from leaching in a flat-lying humid setting, later subjected to a high water table and coal formation (Percival, 1986; Buol et al., 1989; Allen and Wright, 1989). They form on sandy parent material in relatively well-drained sites within waterlogged, hydromorphic, low-relief delta plains (Percival, 1986). The leaching of all but the white quartz and kaolinite components is aided by the presence of abundant acidic coniferous vegetation in a humid climate, hence their occurrence beneath coals (Percival, 1986). Gymnosperms continued to dominate Upper Cretaceous floras (Frank, 1999) and are prime constituents of Horseshoe Canyon Formation coals. Among various examples in the Horseshoe Canyon, a very prominent spodic horizon is present at the top, known as the "Whitemud sandstone".

All types of coal, which originate as waterlogged surfaces containing very high concentrations of organic matter, are named "histosols". Histosols are present as coal seams throughout much of the Horseshoe Canyon Formation, especially in the East Coulee, Hoodoo, and Carbon tongues. These records of wetland ecosystems likely represent fens (water and nutrients incorporated through both rainfall and groundwater sources) (Frank, 1999) on the Horseshoe Canyon delta plain where peat was deposited close to mean sea level. Many histosols are underlain by gleysols, or albic horizons associated with spodosols.

Paleosols in alluvial settings. Paleosols were an integral part of the landscapes of ancient floodplains where sporadic overbank deposition and exposure was important (Kraus and Aslan, 1999). The continuous operation of soil-forming processes and the development of soils is expected in all alluvial settings on an ongoing basis; most successions *should* have numerous superposed similar soil profiles (Kraus and Brown, 1986). In an alluvial system, both erosion and deposition are highly episodic, together occupying very little of the total time represented by the preserved succession; the correct interpretation of alluvial successions is one of long intervals of stasis with prolonged pedogenesis, punctuated by very brief and infrequent intervals of deposition or erosion (Kraus and Brown, 1986). Hence most floodplain successions comprise numerous, stacked, moderately developed, fine-grained paleosol horizons, punctuated by lesser, coarser grained channel and splay deposits (Kraus and Brown, 1986). As detailed below, this is a good description of large parts of the Horseshoe Canyon Formation.

The style of paleosol development and its preservation potential are directly linked to the speed and continuity of sediment accumulation on the floodplain relative to the rate of pedogenesis (Kraus, 1999). If there is no erosion and a steady rate of sedimentation, then thick cumulative paleosols (thick, immature to moderately mature single gleysol or vertisol types) will develop; if there is no erosion but a rapid and unsteady rate of sedimentation, then compound paleosols will accumulate (thinner, weakly developed multiple vertisol or calcisol types separated by non-pedogenic sediments); if the rate of pedogenesis is greater than the rate of deposition in any setting, then composite paleosols will develop (stacked, mature paleosols displaying well-developed horizonation) (Kraus, 1999). If paleosols are completely separated by other deposits and well-differentiated, then this suggests that subsidence and sedimentation were fairly rapid (Retallack, 1981; Kraus and Aslan, 1999), a condition reflected by the Horseshoe Canyon Formation. In the middle floodplain, the more rapid the aggradation, the less reddened, the less calcic and the less mature will be the paleosol (Allen and Wright, 1989). However, toward the coastal margin rapid aggradation may occur but drainage is poor, and drab burrowed gleysols will dominate (Allen and Wright, 1989), as they do in much of the Horseshoe Canyon.

Paleoclimatic interpretation of paleosols. Paleosols can be used to reconstruct ancient climates: each shift to drier climate results in more mature paleosols and more alluvial dissection; each shift to a more humid climate results in less mature paleosols and more alluvial aggradation (Allen and Wright, 1989). Within a floodplain succession, drab-coloured soils are characteristic of low-lying landscapes where oxygen is excluded as a result of waterlogging, and complexes of clay and organic matter dominate, even in well-drained vertisols (Retallack, 1986). Under the reducing conditions in swampy land, iron remains in the reduced state and pedogenic horizons contain abundant drab-coloured chlorite, pyrite and siderite (Retallack, 1986). Spodosols, histosols, sideritic calcisols and gleysols (all common in the Horseshoe Canyon) are more typical of humid midlatitude paleoclimates; calcitic calcisols are indicative of dry, subtropical paleoclimates (Kraus, 1999), and occur in the Horseshoe Canyon Formation only in the Tolman tongue.

DESCRIPTIONS AND INTERPRETATIONS OF HORSESHOE CANYON FACIES

Middle-upper Bearpaw facies

In this study, facies of the middle–upper Bearpaw Formation are represented as tongues in the Strathmore core, and in outcrops at West Dorothy, East Coulee and the Hoodoos, as well as in numerous well logs. These deposits are dominated by grey to brownish grey, burrowed mudstone with interbedded siltstone and very fine-grained sandstone, characteristically arranged in distinct coarsening-upward sequences 5 to 15 m thick. They are typically sharply overlain by marginal to nonmarine, sandstone-dominated deposits attributable to the Horseshoe Canyon Formation (Fig. 28).

Mudstone is generally brown to brownish grey to grey claystone to silty claystone (Fig. 29), with abundant horizontal and sub-vertical *Planolites*-like burrows. At East Coulee, *Ophiomorpha* burrows are prominent. Units of mudstone generally coarsen upward, with an upward increase of silt content and interbeds of sandstone within sequences, whereas bioturbation decreases upward. The bentonitic content is high throughout, and at West Dorothy, there is a distinctive pale grey weathering bentonite bed 6 m thick, indicating continuous explosive volcanism throughout deposition. Thin, rust-weathering sideritic beds are common. Carbonaceous partings and fragments are common suggesting proximity to nonmarine environments. These deposits, reflecting the norm of deposition in the Bearpaw sea, are interpreted as background, low-energy, mudstone deposited relatively slowly in a shallow-marine setting with normal salinities. Common to abundant infaunal activity confirms an oxygenated environment.

Light grey, very fine- to fine-grained sandstone is a common constituent, occurring in beds between 1 cm and 3 m thick (Fig. 30). These have sharp, commonly scoured bases, sharp tops, may be well sorted, and are commonly burrowed. Horizontal and low-angle lamination are common, with lesser hummocky cross-stratification, trough crossbedding and ripple crosslamination. Carbonaceous partings are common and suggest input from nearby nonmarine settings. The sandstone is interbedded with the

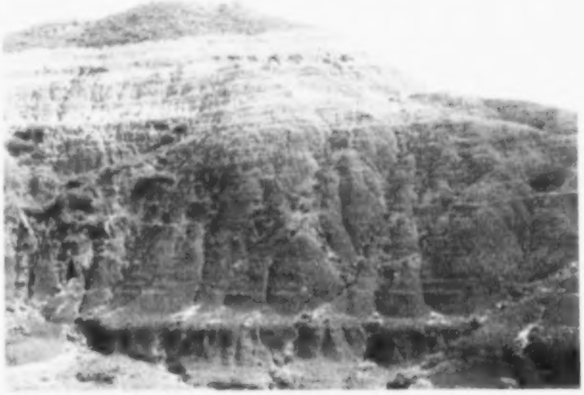


Figure 28. Brownish, bioturbated, marine mudstone of the Bearpaw Formation middle tongue, overlain by interbedded grey sandstone, mudstone and coal of the Hoodoo tongue (West Dorothy). View shows about 40 m of strata (GSC photo no. 4762-4).

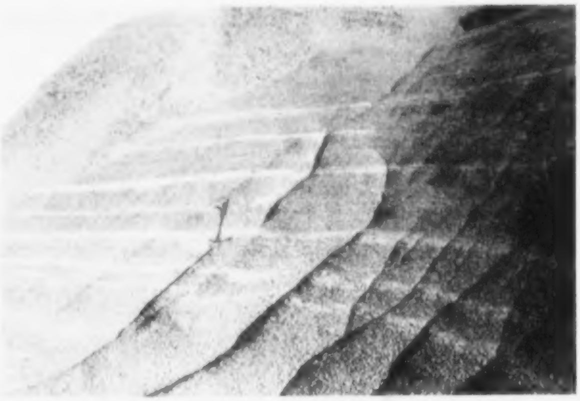


*Figure 29. Typical brownish, bioturbated silty claystone with **Ophiomorpha** burrows and thin, 0–5 cm grey siltstone beds, Bearpaw Formation middle tongue (East Coulee Bridge) (GSC photo no. 4762-5).*

mudstone in stacked coarsening- and thickening-upward sequences (Fig. 31). These deposits are interpreted as recording rapidly emplaced, higher energy events in a shallow-marine or shoreface setting, sourced from clastic input points at the shoreline.

Strathmore tongue facies

Unfortunately, the Strathmore tongue is not exposed in outcrop within the study area because it pinches out into Bearpaw marine shale before this stratigraphic interval rises to the surface in the Red Deer River valley. Therefore the unit is known only from the Strathmore core and well logs. In the core, the Strathmore tongue is represented by 35 m of thinly interbedded, fine-grained sandstone, siltstone, carbonaceous mudstone, and coal. Generally, the deposits coarsen-upward from predominantly burrowed siltstone at the base to sandstone, siltstone and coal at the top, although there is considerable intertonguing of deposits suggesting marine and nonmarine influence.

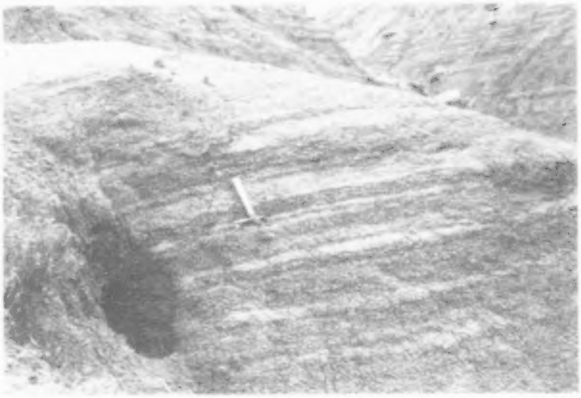


Figure 30. *Thin, grey, sharp-based, very fine-grained sandstone beds interbedded with brownish, bioturbated mudstone, Bearpaw Formation middle tongue (West Dorothy) (GSC photo no. 4762-6).*

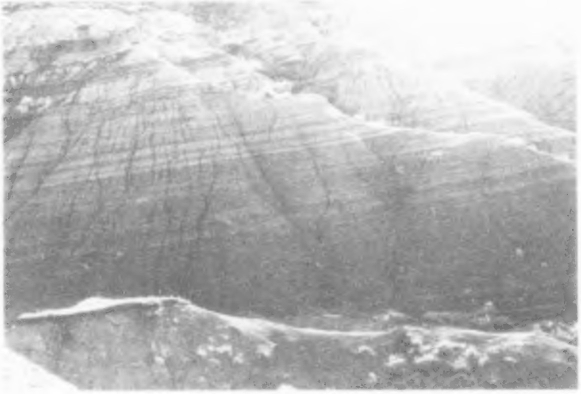


Figure 31. *Thickening- and coarsening-upward sequence at top of the Bearpaw Formation middle tongue, overlain by thicker sandstone of lower Hoodoo tongue (East Coulee Bridge). View shows about 20 m of strata (GSC photo no. 4762-7).*

Sandstone deposits are grey, very fine to fine grained, fine upward and are well sorted, with sharp bases and tops, horizontal lamination and ripple crosslamination. They are typically 0.5 to 3.0 m thick and are generally overlain by siltstone or coal. Near the base of the formation thin sandstone beds have some simple, horizontal burrows. These units are interpreted to represent shallow-marine and shoreface sediments passing upward into floodplain deposits.

Siltstone beds are grey, commonly sandy, coarsen-upward near the base and fine-upward near the top. They have abundant, simple, horizontal and sub-vertical burrows near the base of the formation, but abundant carbonaceous material near the top. Burrowed siltstone near the base is considered to be of shallow-marine origin, whereas carbonaceous siltstone near the top is interpreted to represent nonmarine floodplain deposition.

Thin carbonaceous mudstone and coal beds occur throughout, overlying rooted horizons in places, including near the base of the unit. These deposits overlie burrowed marine mudstone of the Bearpaw, suggesting rapid progradation of a muddy shoreline. There is also a 2 m coal bed at the very top of the member, underlying more marine mudstone of the middle Bearpaw tongue. These histosol deposits are considered to represent nonmarine to brackish marsh sediments, especially well-developed during the period of rapid base level rise related to the succeeding marine transgression.

Hoodoo tongue facies

Facies of the Hoodoo tongue are known from nine outcrops, the Strathmore core and many well logs. These rocks have been well-described and illustrated in great detail in the Willow Creek area by many authors, as mentioned in a previous section of this report. The formation is particularly well exposed at Hoodoos Recreation Area and in all valley walls of the Red Deer River between East Coulee and Drumheller, and in those of Rosebud River between its mouth and Wayne. The unit is typified by interbedded thick sandstone (commonly with IHS), siltstone and abundant thick coal seams (Fig. 32). In general, sandstone beds are thicker and more numerous, siltstone beds are thinner and coals are more dominant than in underlying and overlying strata. The tongue is overlain by the Midland tongue, or the upper Bearpaw tongue.

The sandstone is pale grey, well sorted, generally very fine to medium grained, and occurs in units 1 to 10 m thick (Fig. 33). Units are commonly multistoried, with individual stories separated by scour surfaces and thin, discontinuous units of grey mudstone, and generally fine upward. The bases of fining-upward units are invariably sharp and deeply scoured, with lags of shale rip-ups, wood fragments, coaly chips and reworked caliche or sideritic nodules (Fig. 34, 35). Trough crossbedding is common, with abundant IHS and low-angle lamination (e.g., East Coulee, Hoodoos, Rosedale Bridge) (Fig. 36, 37). At East Coulee and Hoodoos, thick, multistoried sandstone channel bodies sharply overlie marine, mudstone-dominated deposits of the Bearpaw Formation (middle Bearpaw tongue) (Fig. 38), and are overlain by thin, coarsening-upward sequences with marine influence. These channel sandstone bodies with evidence of marine influence are interpreted to represent tidally influenced, incised, high-sinuosity valley fills, located at the seaward extremity of a floodplain setting (Fig. 39). Paleoflow was to the southeast (see below).

The siltstone is predominantly greenish grey, muddy or sandy, in units ranging up to 7 m thick, which commonly overlie sandstone bodies and fine upward. Some are rooted at the top and are overlain by coaly beds. Especially toward the north and west (farther from marine influence), the most

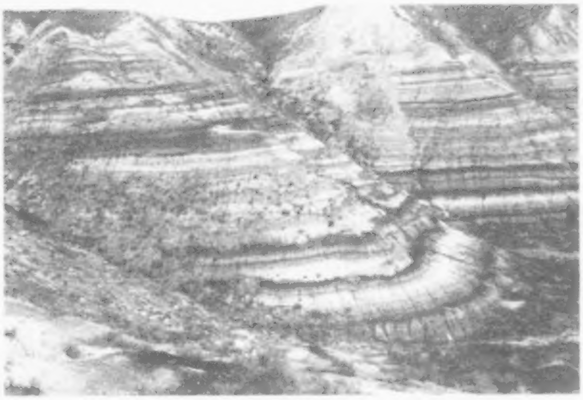


Figure 32. *Interbedded lithologies typical of the Hoodoo tongue including thick, scour-based sandstone with IHS bedding, thinner mudstone and numerous coals (Rosedale Bridge #2). View shows about 65 m of strata (GSC photo no. 4762-8).*

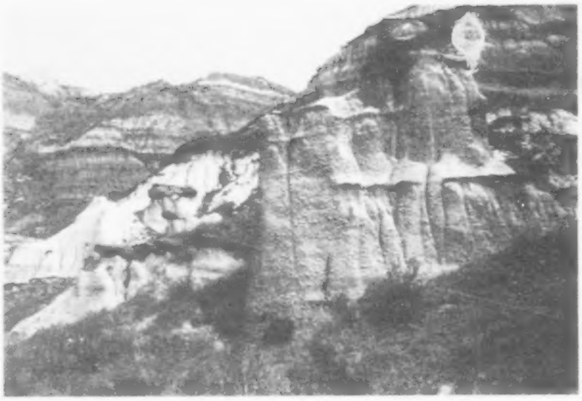


Figure 33. *Pale grey, uniform, fine-grained sandstone in a multistoried channel body 6 m thick, with trough-crossbedding indicating flow to the east. Hoodoo tongue (Wayne) (GSC photo no. 4762-9).*

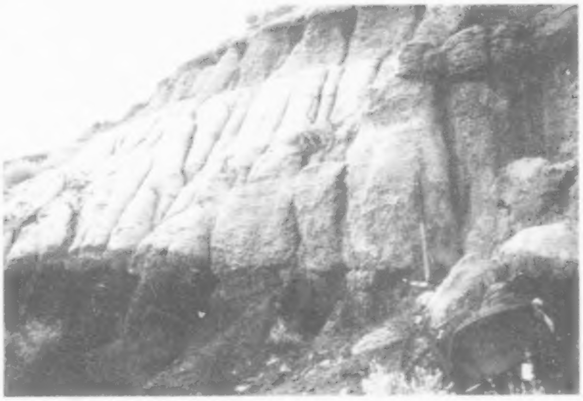


Figure 34. *Sharp-based, fining-upward, fine- to medium-grained sandstone 2 m thick, erosively overlying thick coal. Hoodoo tongue. It includes a lag of ripped-up coal and wood fragments, and is overlain by carbonaceous mudstone (Rosedale Bridge #2) (GSC photo no. 4762-10).*

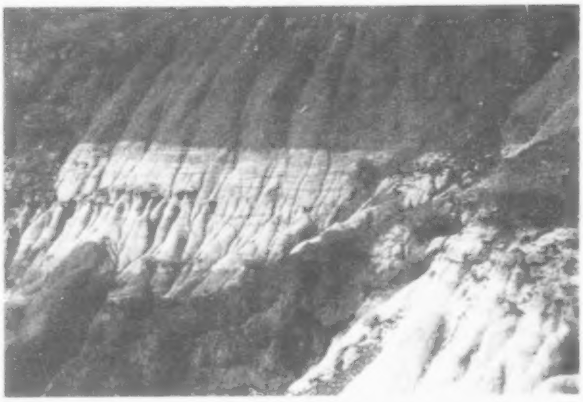


Figure 35. *Deeply scoured base and sharp, flat top of a 5 m fine- to medium-grained sandstone channel, upper Hoodoo tongue (Drumheller East) (GSC photo no. 4762-11).*

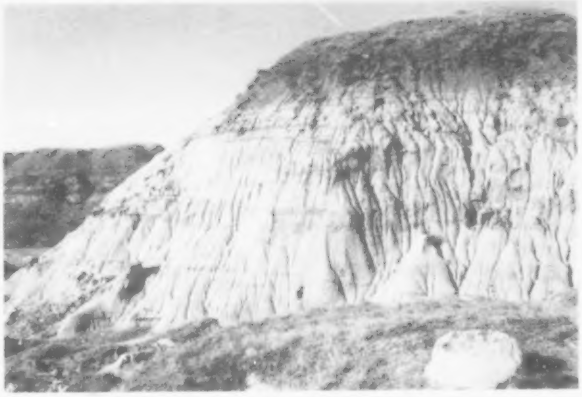


Figure 36. Fine-grained sandstone channel body, 10 m thick, with abundant trough-crossbedding and IHS bedding, fining upward to coal, base of Hoodoo tongue (Hoodoos) (GSC photo no. 4762-12).

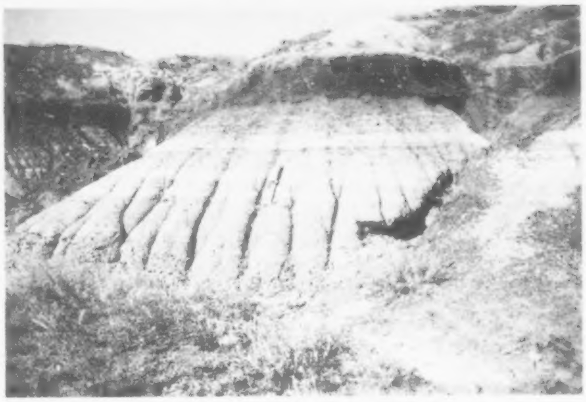


Figure 37. Thinly interbedded sandstone and siltstone in an IHS-dominated unit, overlain by thick coal, upper Hoodoo tongue (Drumheller East) (GSC photo no. 4762-13).

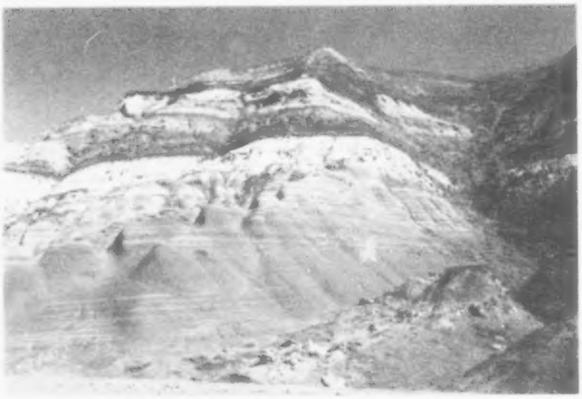


Figure 38. Bioturbated marine mudstone of Bearpaw Formation middle tongue, overlain by pale grey sandstone and coal of lower Hoodoo tongue (East Coulee Bridge). View shows 50 m of strata (GSC photo no. 4762-14).

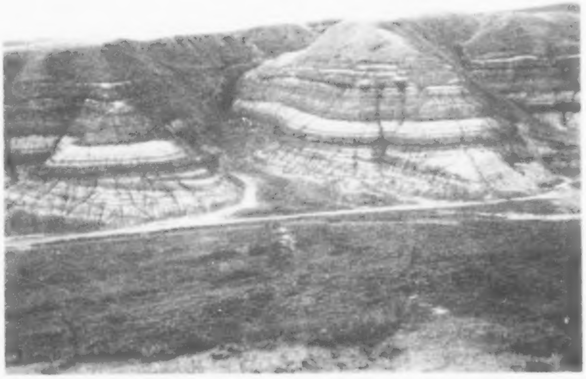


Figure 39. IHS sets dipping northward and northeastward within large, meandering incised valley, lower Hoodoo tongue (Hoodoos/Willow Creek). View shows about 50 m of strata (GSC photo no. 4762-15).

distinctive aspect of these deposits is their consistent, massive, blocky, rubbly nature, interpreted as the manifestation of pedogenic homogenization processes (e.g., Wayne, Jewel Mine, Drumheller South). These are interpreted as vertisols, dominated by pedoturbation and the shrink and swell dynamics of expandable clays, and support deposition in a low-slope, poorly drained setting with a distinct drying season. In addition, thin, 10 to 50 cm horizons of, and widely dispersed scatterings of rusty-coloured sideritic nodules and concretions are ubiquitous, interpreted as gleysol and calcisol horizons formed under poorly drained conditions (Fig. 40). Individual concretions may range up to 60 cm and include wood fragments and roots. However, in sections toward the south and east (closer to marine influence), the siltstone tends to be brownish grey, may carry roots and/or shell fragments and burrows, and shows less evidence of pedogenesis (e.g., East Coulee, Hoodoos).

Thick, 50 to 150 cm, pale greenish or brownish grey, bentonitic, clay-rich mudstone beds are present at some sections (e.g., Aerial Suspension Bridge, Highway 9) associated with coal and carbonaceous beds, and are interpreted as volcanic ash-fall beds.

Coal seams (histosols) are prominent components of the Hoodoo tongue, occurring as black, lignitic to vitreous beds up to 3 m thick (e.g., Aerial Suspension Bridge, Highway 9). Most have sharp rooted bases and tops, with minor muddy partings. Others grade upward from, or upward into, dark grey carbonaceous mudstone. Dark grey, carbonaceous mudstone beds up to 3 m thick, with thin coaly streaks and wood fragments are also common. Close associations with bentonites and thick sandstone bodies displaying IHS bedding is common. Coal seams and carbonaceous mudstone comprise up to 30 per cent of the strata in the Hoodoo tongue (e.g., Rosedale Bridge, Strathmore core) and are especially common at the top (Fig. 41). These deposits are interpreted to represent sedimentation in marshes on the low-lying, subsiding, marginal floodplain.

Braman et al. (1995) recorded the presence of thick oyster shell bars oriented southwest-northeast (parallel to paleoshorelines), common burrows and borings including *Ophiomorpha* (Fig. 42), and rare shark teeth and fish bones, emphasizing the importance of marine influence. Dinosaur bones are not common, but large, in situ coniferous stumps and roots are present (Shepheard et al., 2000).

Midland tongue facies

Facies of the Midland tongue have not been well described before. In this study they are known from 22 measured sections, the Strathmore core, and many well logs. The formation is particularly well exposed at Orkney Hill and at Wayne, in all valley walls of the Red Deer River between Midland Provincial Park and Morrin Bridge, and the valley walls of Rosebud River between Wayne and Beynon and Kneehills Creek between its mouth and Hesketh. The unit is typified by thinly interbedded sandstone, siltstone and coal (Fig. 43). In general, sandstone units are thinner, siltstone units are thicker and more numerous, and coal is less dominant than in underlying strata. The formation is overlain by the non-coaly Tolman tongue (Fig. 44), or the Drumheller marine tongue.

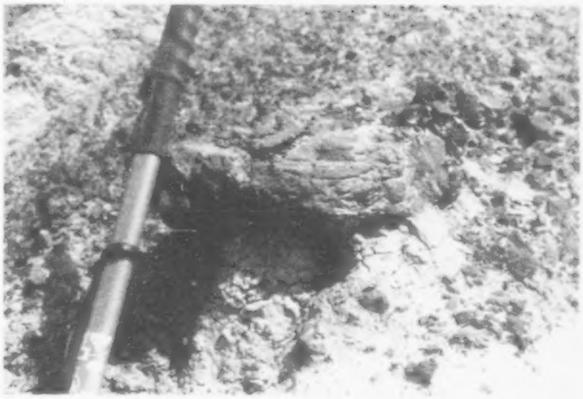


Figure 40. *Irregular sideritic concretion bed (calcisol) with roots and wood fragments, at the top of a thick sandstone body, upper Hoodoo tongue (Wayne) (GSC photo no. 4762-16).*

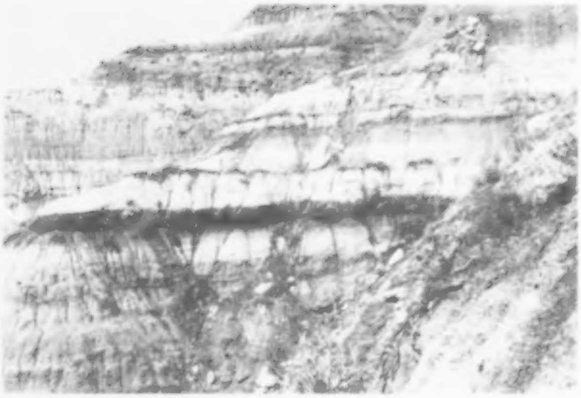


Figure 41. *Thick, laterally continuous 1 m coal seam (histosol) at the top of the Hoodoo tongue Member, overlain by strata of the Midland tongue (Wayne) (GSC photo no. 4762-17).*

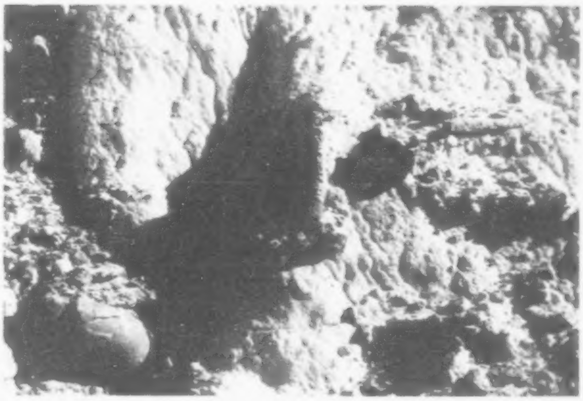


Figure 42. *Vertical* ***Ophiomorpha*** *burrows, with subhorizontal* ***Planolites*** *burrows, in tidally influenced channel sandstone, lower Hoodoo tongue (East Coulee Bridge) (GSC photo no. 4762-18).*

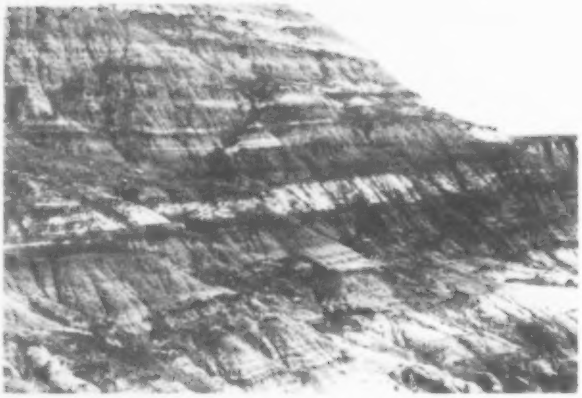


Figure 43. *Thinly interbedded grey sandstone, siltstone, and minor coal, typical of the Midland tongue (Jewel Mine). View shows about 25 m of strata (GSC photo no. 4762-19).*

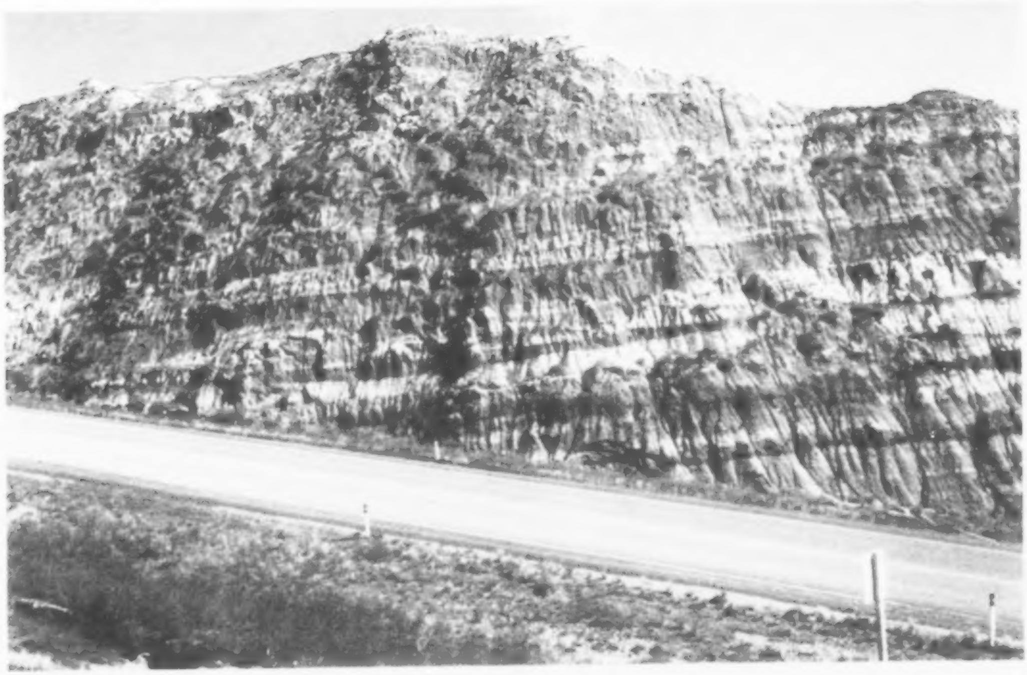


Figure 44. *Thinly interbedded grey sandstone, siltstone, and minor coal of the Midland tongue, overlain by uniform greenish pedogenic siltstone of the Tolman Member (Bleriot Ferry). View shows about 20 m of strata (GSC photo no. 4762-20).*

The sandstone is pale grey, well sorted, very fine to coarse grained, generally fine to medium, and occurs in units 1 to 6 m thick. Units are commonly multistoried, with individual stories separated by scour surfaces or by thin, discontinuous units of greenish grey siltstone, and they generally fine-upward (Fig. 45). Bed bases are invariably sharp, and typically scoured, with lags of shale rip-ups, wood fragments, coaly chips, dinosaur bone fragments and reworked caliche or sideritic nodules (Fig. 46). Trough crossbedding is universal (Fig. 47), with abundant low-angle lamination, ripple crosslamination, and inclined bedding. Rare IHS occurs near the base and top (e.g., Highway 575, Morrin Bridge, Mile 64.5). Many sandstone bodies have deeply incised erosional bases and laterally extensive channel geometries up to 50 m across (e.g., Highway 9, Highway 575, Jewel Mine) (Fig. 48). Several examples have erosionally scoured tops, filled with overlying pedogenic siltstone (e.g., Bleriot Ferry, Jewel Mine) (Fig. 49). Some thin occurrences, encased in pedogenic siltstone, are manifest in laterally extensive outcrops as thin lenses up to 50 m across with erosional bases (e.g. Mile 64.5, Dunphy Cemetery) (Fig. 50). These sandstone bodies are interpreted to represent fluvial, probably high-sinuosity, channel and overbank splay deposits, embedded in a floodplain setting. Paleoflow was to the east-southeast (see below).

The siltstone is greenish grey, commonly sandy, and occurs in units ranging up to 4 m thick, which commonly overlie sandstone bodies and fine upward. Thin, dark grey, carbonaceous mudstone beds are common and some are rooted at the top (e.g., Orkney, Morrin Bridge, Jewel Mine). The most distinctive aspect of these deposits is their

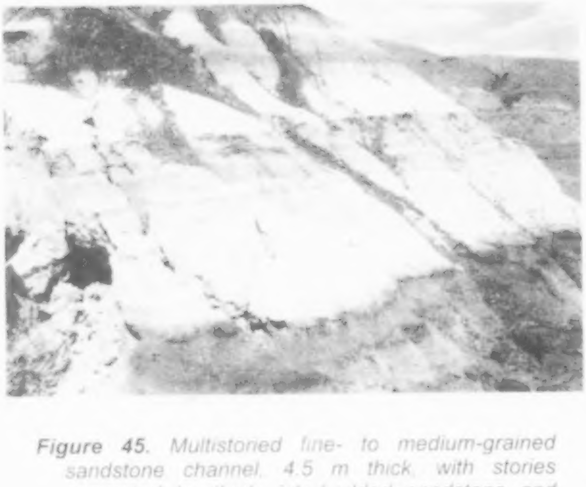


Figure 45. *Multistoried fine- to medium-grained sandstone channel, 4.5 m thick, with stories separated by thinly interbedded sandstone and siltstone, upper Midland tongue (Range Road 21-4) (GSC photo no. 4762-21).*

consistent, massive, blocky, rubbly nature, interpreted as the manifestation of pedogenic homogenization processes (e.g., Strathmore Core, Taylor Siding, Wayne, Range Road 21-5, Highway 575) (Fig. 51). These are interpreted as vertisols, dominated by pedoturbation and the shrink and swell dynamics of expandable clays, and suggest deposition in a low-slope, poorly-drained setting with a distinct drying season. In rare occurrences, vertic peds and cutans are visible. In addition, thin, 10 to 50 cm horizons of, and widely dispersed scatterings of rusty-coloured sideritic nodules and concretions are ubiquitous (e.g., Wayne, Taylor Siding, Bleriot Ferry, Morrin Bridge), interpreted as incipient gleysol and calcisol horizons. Individual concretions may range up to 60 cm, have slickensided fracture surfaces and include wood and bone fragments and roots. These characteristics suggest rather poorly drained conditions. Additionally, thin, 0 to 150 cm, pale grey to brownish bentonitic, clay-rich siltstone beds, interpreted as volcanic ash-fall beds, are associated with pedogenic siltstone in a number of outcrops. Dinosaur bones are relatively common in this pedogenic siltstone (e.g. Dunphy, Highway 575).

Coal seams (histosols) are common components of the Midland, occurring as black, lignitic to vitreous beds up to 2 m thick (e.g., Drumheller South, Range Road 21-4, CNR Iron Bridge, Beynon). Most have sharp rooted bases and tops with minor muddy partings. Others grade upward from, or upward into, dark grey carbonaceous mudstone. Coal and carbonaceous mudstone comprise up to 15 per cent of the strata in the Midland tongue (much less than in the underlying Hoodoo tongue). These deposits are interpreted

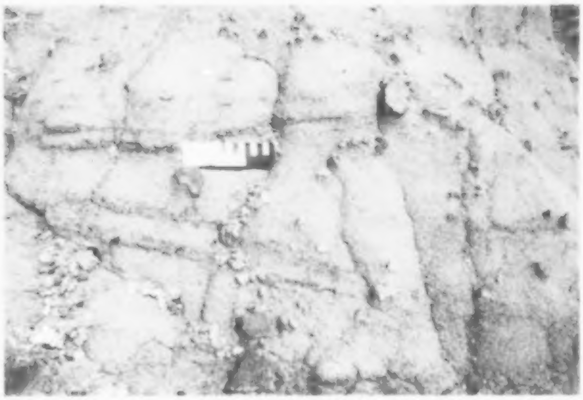


Figure 46. *Lag of small, redeposited caliche nodules in trough-crossbedded, medium-grained sandstone at base of thick channel, middle Midland tongue (Mile 64.5) (GSC photo no. 4762-22).*

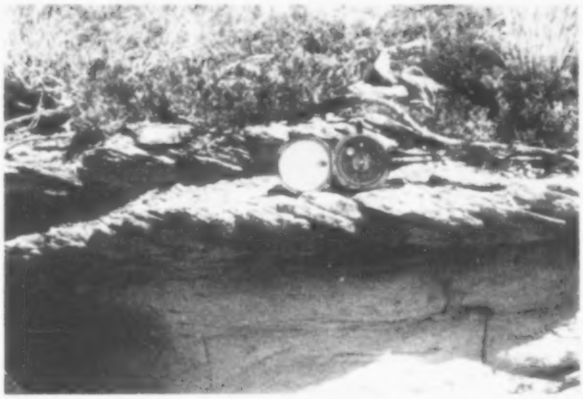


Figure 47. *Trough-crossbed set indicating flow to the east in fine-grained sandstone channel unit 5 m thick, middle Midland tongue (Jewel Mine) (GSC photo no. 4762-23).*

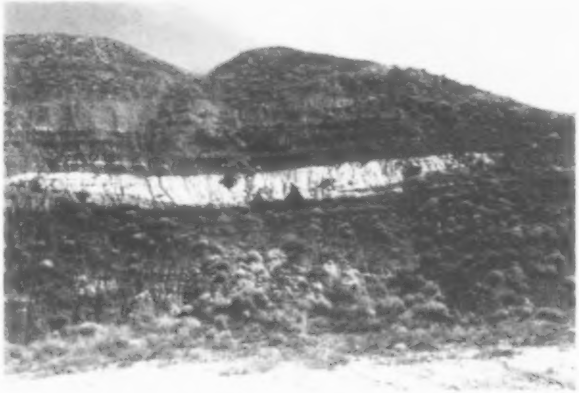


Figure 48. *Broad, shallow (40 x 5.5 m) channel-fill lens of grey, fine- to medium-grained sandstone at base of Midland tongue (Highway #9). View shows about 30 m of strata (GSC photo no. 4762-24).*

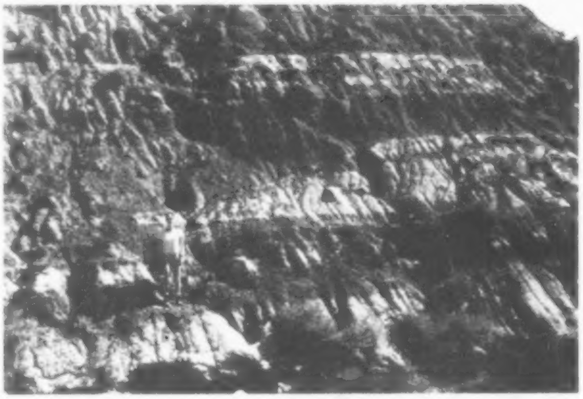


Figure 49. *Greenish grey pedogenic siltstone with calcisol horizons filling scour in trough-crossbedded fine- to medium-grained sandstone 2 m thick, upper Midland tongue (Bleriot Ferry) (GSC photo no. 4762-25).*

to represent sedimentation in marshes on the coastal floodplain, more distal from marine influence than those of the Hoodoo tongue.

In contrast to the bulk of the formation, the lower contact with the underlying Hoodoo tongue is a locus of deposits with apparent marine affinities (here referred to as the upper Bearpaw tongue). At a number of outcrops, in the Rosebud River to Drumheller area, the upper interval of the Hoodoo displays well-developed channelized sandstone bodies with IHS (Rosedale Bridge, Jewel Mine, Drumheller South, Highway 9). At several outcrops similar scour-based channel sandstone beds with IHS also occur above the contact in the lower Midland (Jewel Mine, Drumheller South, Highway 575). More importantly, direct evidence of marine transgression is present in three locations. Typical marine burrows are present in dark sandy siltstone between multistoried sandstone channels within the lower 15 m of the Midland in the Strathmore core, and a brown, calcareous-cemented, fine-grained sandstone with sharp base and top and hummocky cross-stratification occurs at the Hoodoo-Midland contact at Highway 575 (Fig. 52). At Drumheller South, the contact is marked by a 1 m, brown, calcareous-cemented, fine- to medium-grained sandstone with a very sharp, flat top featuring long, vertical *Skolithos* burrows and dessication cracks (Fig. 53). These characteristics are interpreted to represent a discrete regional marine transgression from the south and east, toward the northwest (as far north as Twp. 32 on Red Deer River), at the Hoodoo-Midland contact.

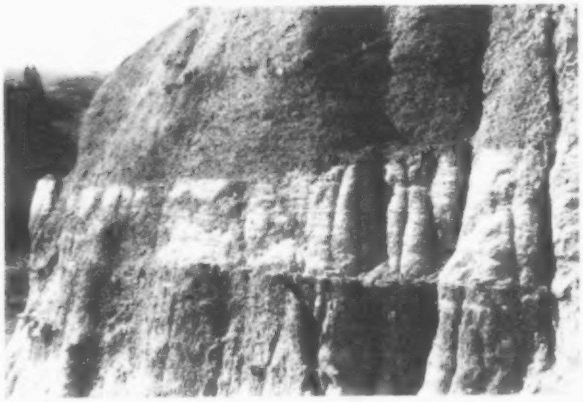


Figure 50*. Pale grey, laterally extensive, sharp-based, fine-grained sandstone splay lens, 1 m thick, encased in overbank greenish grey pedogenic siltstone with calcisol horizons, upper Midland tongue (Mile 70.5) (GSC photo no. 4762-26).*

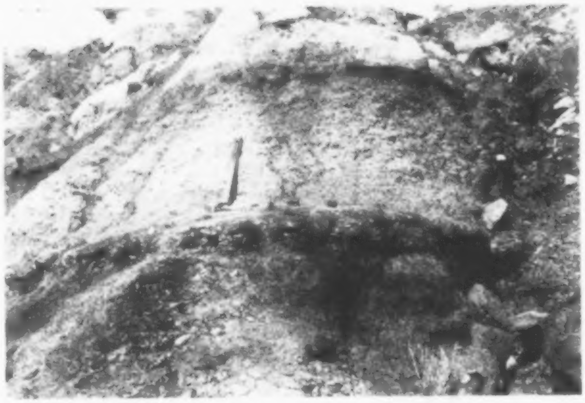


Figure 51*. Greenish grey, massive, blocky, rubbly, pedogenic siltstone (vertisol), underlain and overlain by thin, discontinuous coal seams, middle Midland tongue (Orkney Hill) (GSC photo no. 4762-27).*

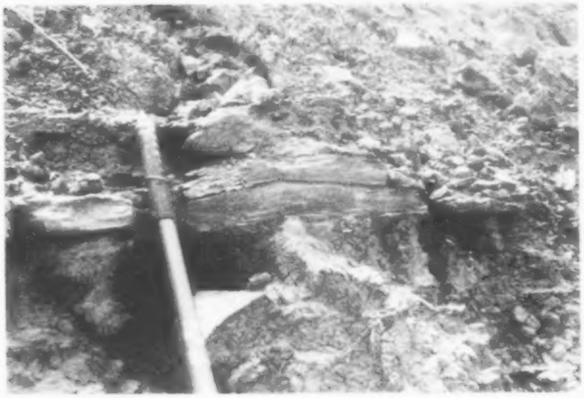


Figure 52*. Hummocky cross-stratification in 1.5 m fine-grained sandstone bed, with sharp, flat base and top, indicating shallow-marine influence at Hoodoo-Midland contact (Highway 575) (GSC photo no. 4762-28).*

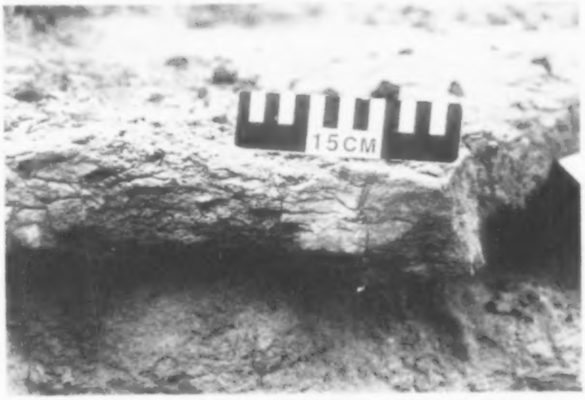


Figure 53*. Vertical* ***Skolithos*** *burrows in a 1 m coarsening-upward, fine-grained sandstone unit, indicating shallow-marine influence at Hoodoo-Midland contact (Drumheller South) (GSC photo no. 4762-29).*

Braman et al. (1995) reported the common occurrence of dinosaur (primarily hadrosaurid) skeletons and bonebeds, attesting to the dominance of terrestrial deposition with little marine influence, except at the base.

Tolman tongue facies

Facies of the Tolman tongue have not been properly described before. In this study they are known from 21 measured sections, the Strathmore core, and many well logs. The tongue is particularly well exposed at Horseshoe Canyon and at Power Line and all valley walls of the Red Deer River between Orkney Hill and Dry Island, the Rosebud River between Iron Bridge and Mile 74, and Kneehills Creek between Dunphy and Sharples. The unit is typified by greenish grey pedogenic siltstone and minor, thinly interbedded sandstone, with virtually no coal (Fig. 54). Indeed, the lack of coal is very distinctive within the generally carbonaceous Horseshoe Canyon Formation and nearly diagnostic. All aspects of the Tolman suggest better-drained conditions with less marshland than the other members, here interpreted to indicate a more proximal setting higher on the Horseshoe Canyon floodplain than that represented by earlier tongues and also representing the most arid climatic conditions within the Horseshoe Canyon Formation (D. Eberth, pers. comm., 2002; see later discussion). In general, siltstone beds are thicker and more numerous and sandstone beds are thinner and less numerous than in underlying or overlying strata. The member is overlain by the Carbon tongue (Fig. 55).

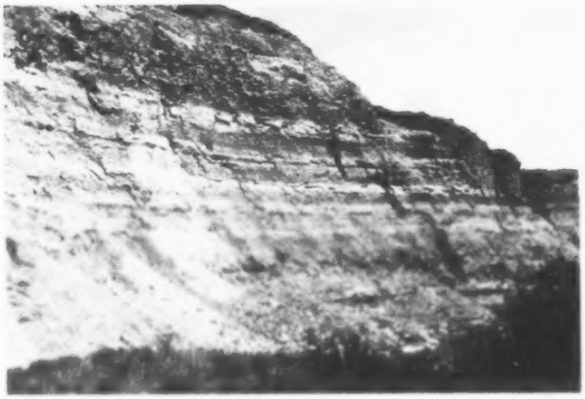


Figure 54. Greenish grey, pedogenic siltstone with thin, very fine- to fine-grained sandstone beds, typical of the Tolman tongue, overlying coal and dark mudstone of the Midland tongue (Range Road 21-5). View shows about 35 m of strata (GSC photo no. 4762-30).

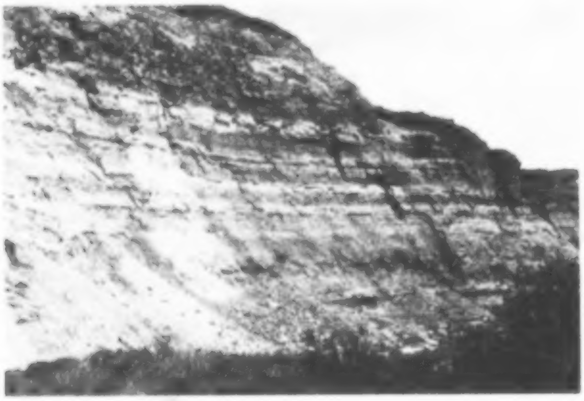


Figure 55. Greenish grey, pedogenic siltstone with thin, very fine- to fine-grained sandstone beds, typical of the Tolman tongue, overlain by dark mudstone and coal of the Carbon tongue (Carbon Gas Plant). View shows about 35 m of strata (GSC photo no. 4762-31).

The siltstone is greenish grey, commonly sandy, in individual units ranging up to 4 m thick, although compound units with thin, sandy beds may range up to 15 m (Fig. 56). Siltstone may overlie sandstone bodies, include many thin sandstone interbeds and fine upward, although thick units with no obvious grain size trend are more common. The most distinctive aspect of these deposits is their consistent, massive, blocky, rubbly nature, interpreted as the manifestation of pedogenic homogenization processes (e.g., Bleriot Ferry, Blue Bridge, Carbon Gas Plant, Horseshoe Canyon) (Fig. 57). These deposits are interpreted as stacked vertisols, dominated by pedoturbation and the shrink and swell dynamics of expandable clays, and suggest a distinct drying season. The siltstone is considered to represent overbank deposits on a fluvial floodplain and makes up about 50 to 60 per cent of the strata of the member. In rare occurrences, vertic peds and cutans are visible. In addition, thin, 10 to 50 cm horizons of, and widely dispersed scatterings of, calcareous and sideritic nodules and concretions are ubiquitous (e.g., Power Line, Blue Bridge, Weismer's RR cut, Horseshoe Canyon, Range Road 21-5), interpreted as incipient calcisol horizons (Fig. 58). Individual concretions may range up to 80 cm, have vertical slickensided fracture surfaces and include wood and bone fragments and roots. At several outcrops, laterally continuous calcrete horizons up to 1 m thick composed of sideritic limestone and medium-grained sandstone beds with sharp irregular tops, more gradational bases and vertical roots are well developed (e.g., Power Line, Tolman Bridge, Blue Bridge, Horseshoe Canyon) (Fig. 59). These are more common in the upper part of the Tolman tongue and are interpreted as well-developed calcisols, representing extensive hiatal surfaces within the floodplain succession, probably signalling more arid climatic conditions than any other part of the Horseshoe Canyon Formation. Uncommonly, thin, 0 to 50 cm, pale

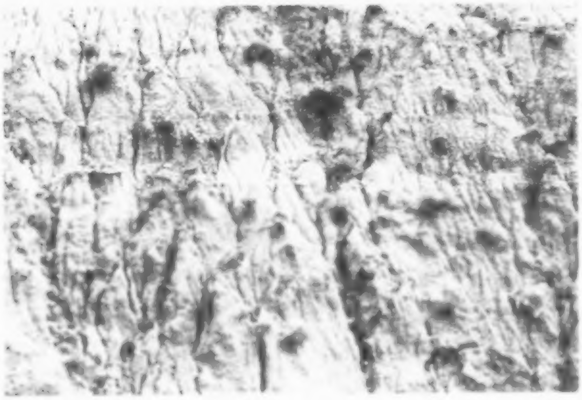


Figure 56. *Greenish grey, massive, blocky, rubbly, pedogenic siltstone (vertisol), on steep bank with modern rill erosion. Tolman tongue (Three Hills Creek). View shows about 2 m of strata (GSC photo no. 4762-32).*

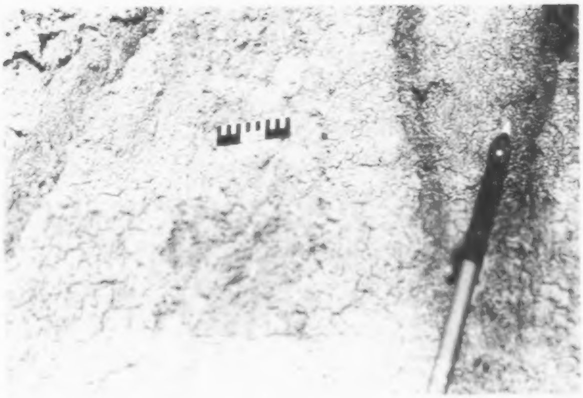


Figure 57. *Massive, blocky, rubbly, pedogenic siltstone (vertisol), with ped structures, typical of the Tolman tongue (Dunphy Cemetery) (GSC photo no. 4762-33).*

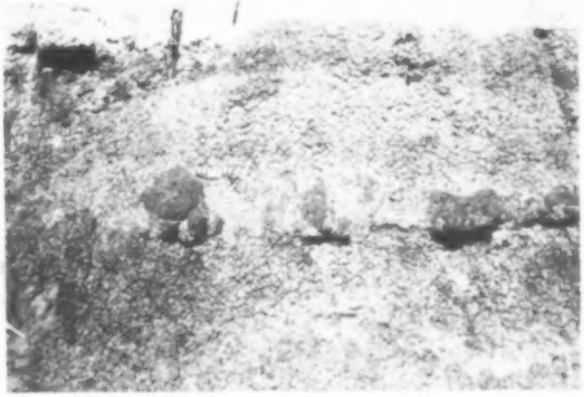


Figure 58. *Laterally continuous, 25 cm, sandy, sideritic horizon with sharp, irregular top and wood fragments, encased in pedogenic siltstone and interpreted as a calcisol horizon. Tolman tongue (Blue Bridge) (GSC photo no. 4762-34).*

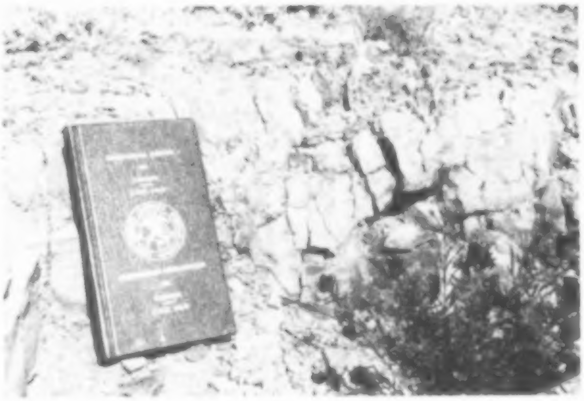


Figure 59. *Laterally continuous, 60 cm, sandy, sideritic calcisol with sharp irregular top, gradational base, vertical fractures and roots. Tolman tongue (Tolman Bridge) (GSC photo no. 4762-35).*

grey to brownish bentonitic, clay-rich siltstone beds, interpreted as volcanic ash-fall beds, are associated with pedogenic siltstone in a number of outcrops. Dinosaur bones are relatively common in these pedogenic siltstone deposits.

The sandstone is pale grey, well sorted, very fine to medium grained, generally fine to medium, occurring in units 0 to 6 m thick. It comprises 40 to 50 per cent of the strata in the Tolman tongue. Units may be thick and multistoried, with individual stories separated scour surfaces, thin discontinuous units of greenish grey siltstone, or horizons of sideritic concretions, and units generally fine upward. Some of these sandstone bodies have deeply incised erosional bases and laterally extensive channel geometries up to 50 m across (e.g., Power Line, Tolman Bridge, Strathmore Core, Appleyard Coulee). Conversely, many sandstone lenses are thin (0–1 m thick) and laterally discontinuous with gradational boundaries, encased in thick units of pedogenic siltstone (e.g., Dry Island, Bleriot Ferry, Mile 74, Weismer's RR cut, Hesketh) (Fig. 60). Bed bases are usually sharp, typically scoured, but lags, if present, are of reworked caliche or sideritic nodules. Trough crossbedding and ripple crosslamination are universal, with abundant low-angle lamination, and minor inclined bedding. Rare IHS occurs near the base (see below). The

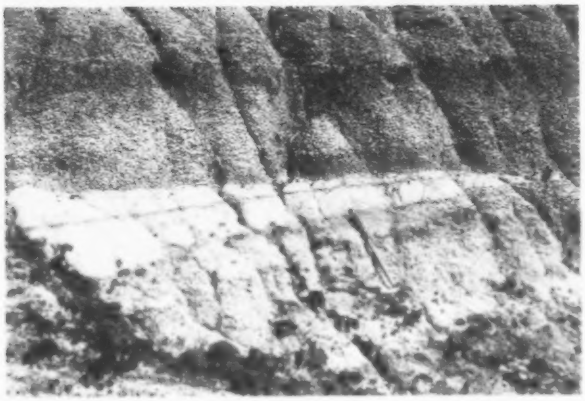


Figure 60. Lenticular fine- to medium-grained sandstone, 1 m thick, with scoured base and flat top, encased in overbank pedogenic siltstone and interpreted as a splay deposit. Tolman tongue (Bleriot Ferry) (GSC photo no. 4762-36).

sandstone is interpreted to represent fluvial, possibly high-sinuosity, channel and overbank splay deposits, embedded in a floodplain setting. Paleoflow was to the southeast (see below).

Lignitic coals and carbonaceous mudstone are particularly rare in this unit, comprising about 2 to 5 per cent of the strata. They are present in only a few outcrops (e.g., Morrin Bridge, Mile 64.5, Range Road 21-5), and are only up to 50 cm thick. They typically comprise gradationally based and sharp-topped carbonaceous mudstone overlying pedogenic, vertisol siltstone, rarely with roots. These deposits are interpreted to represent sedimentation in limited ephemeral marshes on the coastal floodplain, distal from marine or fluvial influence. The distinct lack of coal, so unusual in the Horseshoe Canyon Formation and the hallmark of this unit, reinforces the evidence of the paleosols that the Tolman tongue represents the climax of climatic aridity.

In contrast to the bulk of the member, the lower contact with the underlying Midland tongue is a locus of deposits with clear marine affinities. This represents the strata commonly referred to as the Drumheller marine tongue (Allan and Sanderson, 1945). At several outcrops in the Rosebud River and the Horseshoe Canyon to Morrin Bridge areas the upper strata of the Midland tongue display well-developed channelized sandstone bodies with IHS (Morrin Bridge, Mile 64.5). At several outcrops similar scour-based channel sandstone beds with IHS also occur above the contact in the lower Tolman (Morrin Bridge, Blue Bridge). At Blue Bridge, this IHS unit is capped by a rusty-weathering sideritic bed with an irregular, sharp, upper surface. More importantly, direct evidence of marine transgression is present in four locations. In the Strathmore core, the Midland-Tolman contact is overlain by 1.5 m of fining-upward, fine-grained sandstone with a heavily burrowed top. At Mile 70.5 the contact is marked by 1 m of dark grey, laminated mudstone with wood fragments and oyster shells, capped by a sideritic concretion bed (Fig. 61). At Dunphy Cemetery a 1 m silty mudstone with scattered oyster shells is present right at the top of the outcrop section. Although a section was not measured at Horsethief Canyon for this study, a calcareous oyster shell bed has been noted at the top of the valley wall in previous publications. At the base of the Horseshoe Canyon section, directly above Midland strata, is a 6 m zone of interbedded very fine- to medium-grained sandstone, siltstone and limestone (Fig. 62). These strata contain abundant in situ oyster shells

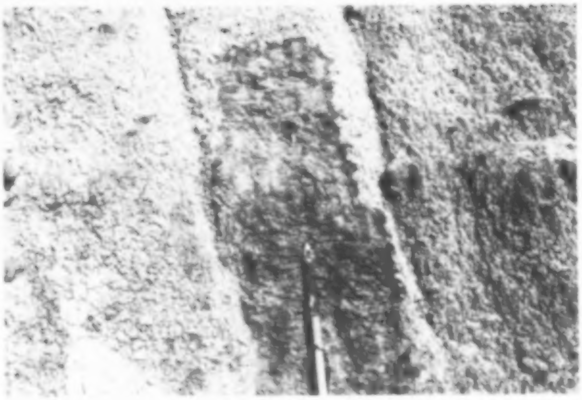


Figure 61. Dark grey, laminated mudstone with wood fragments and oyster shells, capped by thin, sideritic concretion bed and overlain by pedogenic siltstone. Drumheller marine tongue at base of Tolman tongue (Mile 70.5) (GSC photo no. 4762-37).

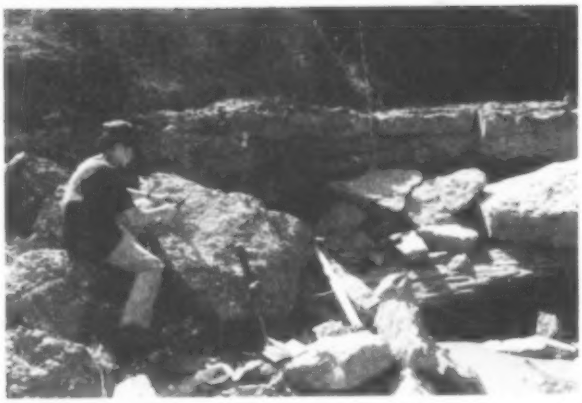


Figure 62. Calcareous, medium-grained sandstone with ripple crosslamination (flow to east), overlain by sandy limestone with abundant oyster shells. Drumheller marine tongue at base of Tolman tongue (Horseshoe Canyon) (GSC photo no. 4762-38).

(Fig. 63). *Planolites* burrows and vertical *Skolithos* burrows (Fig. 64) in a coarse sandy or calcareous matrix. These characteristics are interpreted to represent a discrete regional marine transgression from the south and east, toward the northwest (as far north as Twp. 31 on Red Deer River, and as far west as the Strathmore core), at the Midland-Tolman contact. At the Bleriot Ferry section an anomalous, greenish, sandy siltstone with oyster shells is present 34 m above the Midland-Tolman contact, and in the Strathmore core several burrowed horizons are present higher in the section, possibly indicating additional marine tongues.

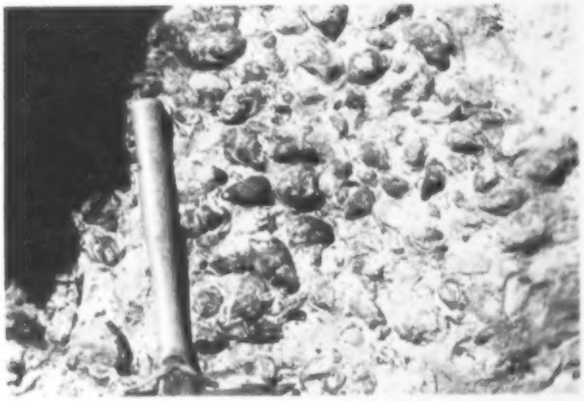


Figure 63. *In situ bivalve shells in sharp-based, calcareous, burrowed, fine-grained sandstone. Drumheller marine tongue at base of Tolman tongue (Horseshoe Canyon) (GSC photo no. 4762-39).*

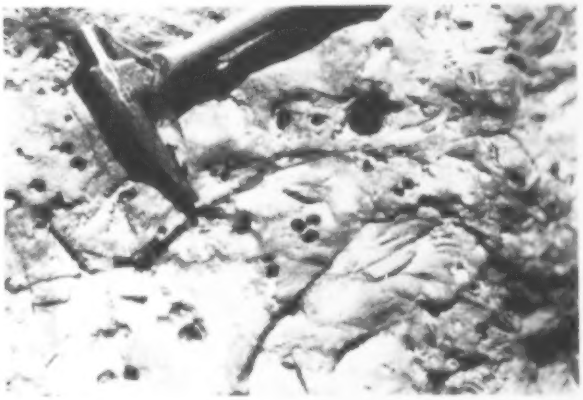


Figure 64. *Abundant vertical* ***Skolithos*** *and subhorizontal* ***Planolites*** *burrows in thin, calcareous, very fine-grained sandstone with oyster shell fragments. Drumheller marine tongue at base of Tolman tongue (Horseshoe Canyon) (GSC photo no. 4762-40).*

Braman et al. (1995) reported dinosaur bones in the Tolman and horizons of in situ and abraded bivalves in the DMT, attesting to the dominance of terrestrial deposition with little marine influence, except at the base. Haglund (2000) studied the invertebrate fauna of the DMT and concluded that it represents a typical estuarine fauna of low salinity and cool temperature conditions. Haglund (2001) further indicated that, during the time of DMT deposition, the geographic distribution of various species suggests a strong marine influence from the south.

Carbon tongue facies

Facies of the Carbon tongue have not been properly described before. In this study they are known from 14 measured sections and many well logs. The tongue is particularly well-exposed at Horseshoe Canyon (Fig. 65) and at Tolman Bridge, and along the walls of the Red Deer River from Bleriot Ferry to Dry Island Provincial Park. The unit is typified by thickly interbedded sandstone, siltstone and coal, and by distinctive white sandstone and dark mudstone members at the top (Fig. 66). In general, the sandstone units are thicker and more numerous, siltstone beds are thinner, and coals are more dominant than in underlying strata. The tongue is sharply overlain by black mudstone of the Battle Formation or thick, brownish-yellowish, coarse-grained sandstone and brightly coloured muddy siltstone of the Scollard Formation (Fig. 67).

The sandstone is pale grey, well sorted, very fine to coarse grained, generally fine to medium, occurring in units 1 to 7 m thick. Units are commonly multistoried, with individual stories separated by thin, discontinuous units of grey mudstone, and generally fine upward. Bed bases are

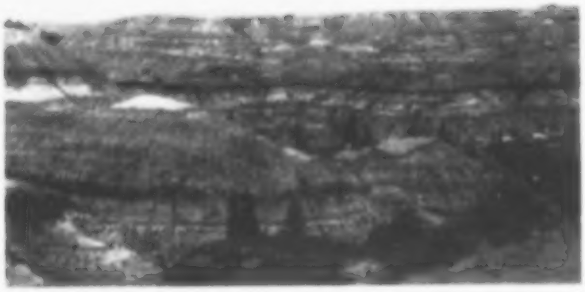


Figure 65. *Interbedded thick sandstone, siltstone and coal, typical of the Carbon tongue (Horseshoe Canyon). View shows about 70 m of strata (GSC photo no. 4762-41).*

invariably sharp (Fig. 68), commonly scoured, with lags of shale rip-ups, wood fragments, coaly chips, and reworked caliche or sideritic nodules. Trough-crossbedding is universal (Fig. 69), with minor ripple crosslamination, low-angle lamination and inclined bedding. Rare IHS is present at the base in several southern outcrops (e.g., Horseshoe Canyon). Some thin occurrences, encased in pedogenic siltstone, are manifest in laterally extensive outcrops as thin lenses up to 50 m across with erosional bases (e.g., Rosebud). Near the top of the Carbon in many outcrops (e.g., Dry Island), are distinctive 3 to 7 m white to yellowish white, well-sorted, simple or multistoried sandstone bodies with scoured bases and lags of calcrete nodules, formerly named the Whitemud Formation. These sandstone bodies are interpreted to represent fluvial, probably high-sinuosity, channel and splay deposits, embedded in a floodplain setting. The white, kaolin-rich sandstone, underlying an organic-rich unit (Battle Formation) (Fig. 70) is analogous to the albic ganister units (spodosols) common in coal-bearing sequences, representing near-surface diagenetic leaching of material during pedogenesis in a flat-lying, subsiding, humid setting with a high water table. The albitization of the Whitemud suggests that the unconformably overlying, organic-rich sediments of the Battle Formation were present at the time the sandstone was within the spodic pedogenic horizon.

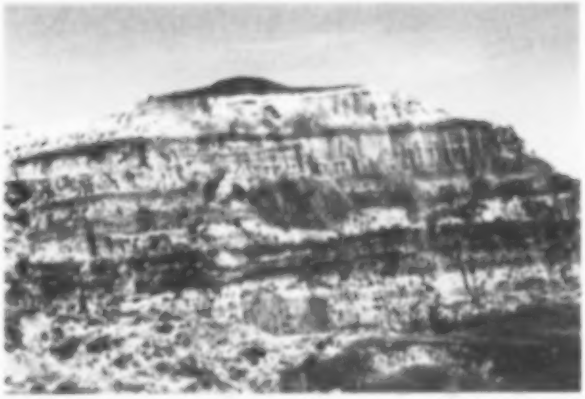


Figure 66. *Thickly interbedded pale grey sandstone, dark siltstone and coal, with the distinctive white sandstone of the Carbon tongue at the top overlain by black mudstone of the Battle Formation (Tolman Bridge). View shows about 85 m of strata (GSC photo no. 4762-42).*

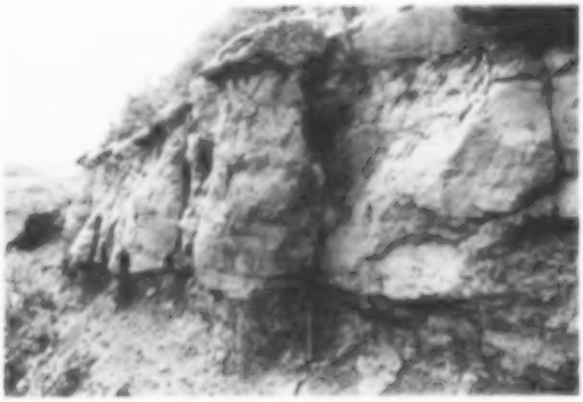


Figure 67. *Thick, yellowish, coarse-grained sandstone of the basal Scollard Formation, sharply overlying dark grey mudstone of the Battle Formation (Three Hills Creek) (GSC photo no. 4762-43).*

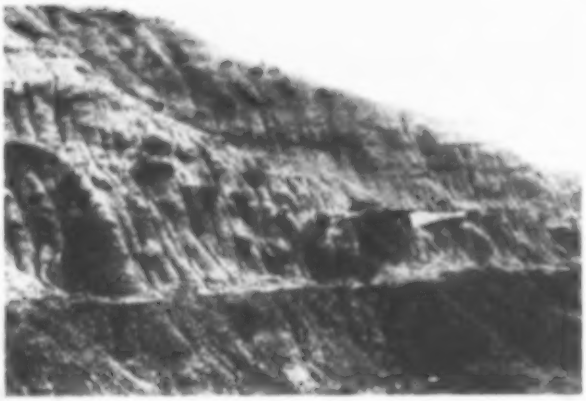


Figure 68. *Multistoried, pale grey, fining-upward, fine- to medium-grained sandstone channel 5 m thick, with sharp, flat base, overlying pedogenic siltstone, and overlain by carbonaceous mudstone. Carbon tongue (Horseshoe Canyon) (GSC photo no. 4762-44).*

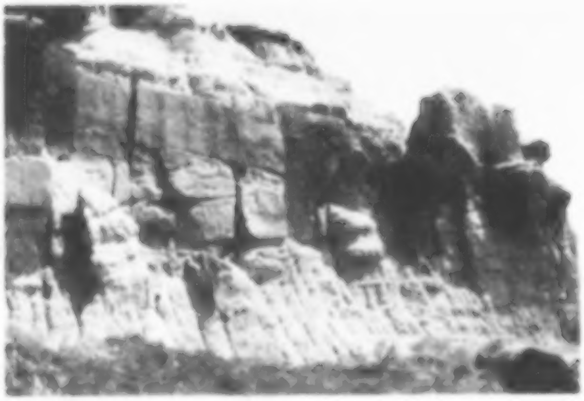


Figure 69. *Trough-crossbed sets (flow to southeast) in fine- to medium-grained sandstone channel unit, 2 m thick. Carbon tongue (Dry Island Provincial Park) (GSC photo no. 4762-45).*

The siltstone is greenish grey to dark grey, commonly muddy or sandy, in units ranging up to 4 m thick, which commonly overlie sandstone bodies and fine upward. Many are rooted at the top. The most distinctive aspect of these deposits is their consistent massive, blocky, rubbly nature, interpreted as the manifestation of pedogenic homogenization processes. In rare occurrences, vertic peds and cutans are visible within these vertisols. In addition, thin, 10 to 50 cm horizons of, and widely dispersed scatterings of, rusty-coloured sideritic nodules and concretions are ubiquitous (e.g., Appleyard Coulee, Horseshoe Canyon), interpreted as gleysol and calcisol horizons. Individual concretions may range up to 60 cm and include wood fragments and roots (Fig. 71). Additionally, thin, 0 to 50 cm, pale grey, bentonitic, clay-rich siltstone beds are uncommonly associated with pedogenic siltstone, interpreted as volcanic ash-fall beds.

Coal seams (histosols) are prominent components of the Carbon, occurring as black, lignitic to vitreous beds up to 2 m thick (e.g., Carbon East, Tolman Bridge) (Fig. 72). Most have sharp rooted bases and tops with minor muddy partings. Others grade upward from, or upward into, dark grey carbonaceous mudstone. Coal and carbonaceous mudstone comprise up to 20 per cent of the strata in the Carbon tongue. These deposits are interpreted to represent sedimentation in marshes on a subsiding waterlogged floodplain, more low-lying than that of the underlying Tolman tongue.

Braman et al. (1995) noted the presence of plant fossils, but no dinosaur finds are presently known from strata of the Carbon tongue.

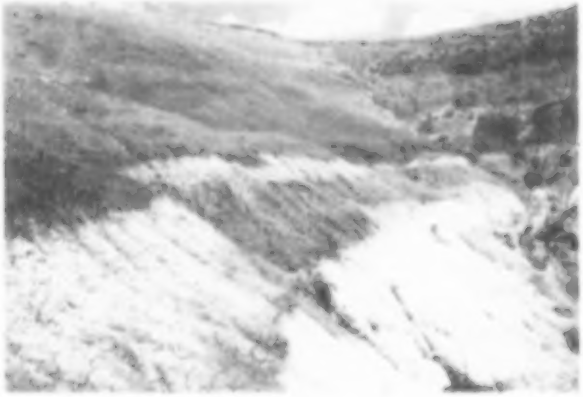


Figure 70. *White, albitized, quartz-kaolin, fining-upward, fine-grained sandstone (2 m thick) of the Whitemud sandstone (interpreted as a spodosol) at the top of the Carbon tongue, overlain by 10 m of black, bentonitic, organic-rich mudstone of the Battle Formation, with the pale grey Kneehills Tuff Zone near the base (Horseshoe Canyon) (GSC photo no. 4762-46).*

The deposits of the Carbon tongue are unconformably overlain by black, bentonitic, organic-rich mudstone of the Battle Formation (Fig. 73), which also includes the Kneehills Tuff, dated at approximately 66–67 Ma (Fig. 74).

Previously recorded paleocurrent data

There is a general paucity of paleocurrent data for the Horseshoe Canyon Formation, except for limited stratigraphic intervals in a few specific areas where modern sedimentological studies have been conducted. The underlying Bearpaw shale is thickest to the east and south, and thins and pinches out to the north and west near Edmonton, although the Bearpaw sea also apparently

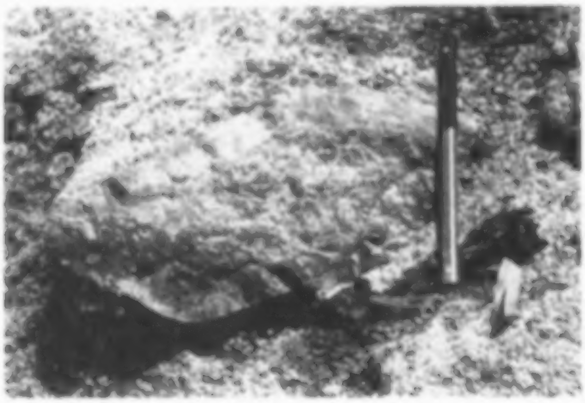


Figure 71. *Giant, 60 cm sideritic concretion with wood fragments and septarian crack network, part of a laterally extensive, rooted calcisol horizon, overlain and underlain by pedogenic siltstone, Carbon tongue (Rosebud) (GSC photo no. 4762-47).*

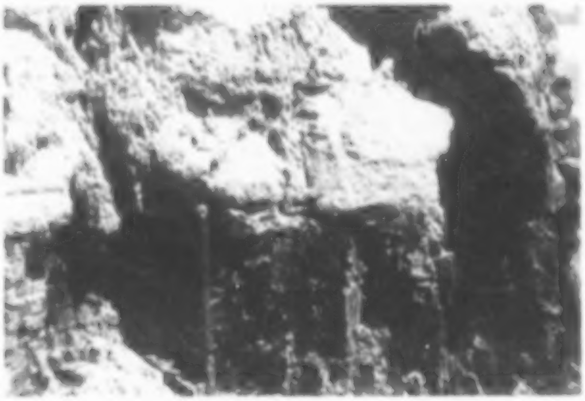


Figure 72. *Thick, laterally continuous, 1.5 m coal (histosol) ("Carbon Seam", #11), overlain by erosively based medium-grained sandstone with lag of coal and wood fragments, lower Carbon tongue (Carbon East) (GSC photo no. 4762-48).*

flooded the area north of Peace River Arch (Caldwell, 1968; Stelck et al., 1976). When it withdrew, it did so toward the south and southeast (Rahmani and Schmidt, 1975). The lowermost 60 m of the Horseshoe Canyon Formation in the Drumheller area has been intensively studied several times in the past 30 years. Shepheard and Hills (1970) suggested that the shorelines were oriented north-south and sediment was supplied from west to east. From heavy mineral analysis Rahmani and Lerbekmo (1975) concluded that sediment dispersal proceeded from the northern and central British Columbia area to the east or southeast in central Alberta. Rahmani (1983) provided the most comprehensive treatment of the Bearpaw-Horseshoe Canyon transition in this area and described the following paleocurrent relations. Most channel-related sedimentary structures indicate flow to the southeast or south-southeast (although some near the base have northeastward flow), interpreted to represent shorelines with a west-southwest–east-northeast trend. Open sea was to the southeast, backbarrier areas were to the northwest and successive progradations extended farther to the southeast through time. Hamblin (1998a) presented a detailed measured section and paleocurrent data from the Little Bow River illustrating that the Bearpaw-Horseshoe Canyon transition was typified by southeastward transport, but overlying and intertonguing St. Mary River Formation facies underwent northeastward transport. In the upper Horseshoe Canyon Formation, a small body of data indicates that sandstone channel units trend northwest–southeast, in a paleodrainage system with flow from the northwest (Nurkowski, 1980; Nurkowski and Rahmani, 1984), complementing the conclusions of Rahmani (1983).

The comparable marine-nonmarine transition in the southern Foothills is represented by the Bearpaw-Blood Reserve-St. Mary River transition. Lerand (1983) suggested the Blood Reserve shoreline was oriented northeast-southwest with offshore to the southeast, as at Drumheller. In the same area a more detailed study by Nadon (1988) delineated a much more complex setting, with tidal channels in the Blood Reserve Formation flowing to the northeast, while overlying St. Mary River fluvial channels flowed north or northeast, suggesting a totally different depositional system from that of the Horseshoe Canyon. Nadon (1988) delineated sources of Bearpaw-age sandstone to the north, west and south of a deeply subsiding marine trough trending east-west, centred on Twp. 4, as the main control on sedimentation in the area. Hamblin (1998d) provided a body of 243 measurements from the complete St. Mary River Formation on Oldman River near Monarch, indicating sediment dispersal to the northeast, again suggesting that the Horseshoe Canyon and the St. Mary River represent completely different, but partly coeval, depositional systems, originating from different source areas.

In the central and northern Foothills, Jerzykiewicz and Labonte (1991) summarized their paleocurrent data for the entire post-Colorado succession, including 146 readings from the St. Mary River-upper Brazeau sequence, mostly of trough crossbedding from fluvial channels. These indicate a diverse paleodrainage pattern, but most give paleoflow to the southeast quadrant. Some actually define flow components to the southwest, suggesting the drainage area extended much farther west than the present edge of the deformed belt, and the authors caution that paleoflow directions may have been different in the Plains beyond their study area (Jerzykiewicz and Labonte, 1991).

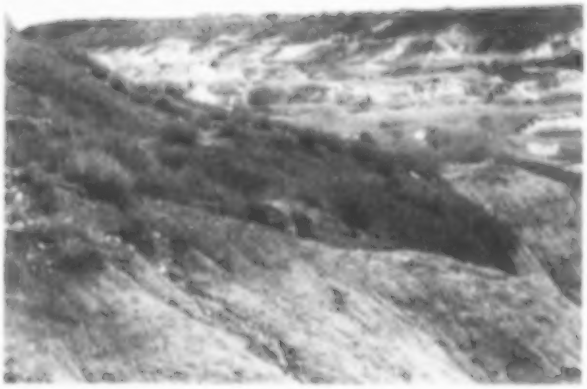


Figure 73. *Uniform, black, bentonitic, organic-rich mudstone of the Battle Formation, with thin, pale grey Kneehills Tuff in the middle, overlying the Carbon tongue (Dry Island Provincial Park). View shows about 6 m of strata (GSC photo no. 4762-49).*

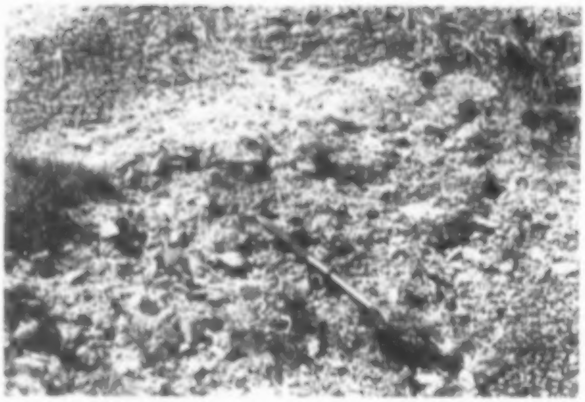


Figure 74. *Pale grey, uniform, hard, vesicular Kneehills Tuff claystone, 50 cm thick, which breaks with a conchoidal fracture, at the top of the Battle Formation and overlain by pedogenic siltstone and basal Scollard Formation sandstone (Horseshoe Canyon West)(GSC photo no. 4762-50).*

New paleocurrent data

The general thickness trends mapped show that the various marine tongues that extend into the Horseshoe Canyon Formation thin from the marine basin in the east-southeast toward the west-northwest. Intertonguing, sandstone-dominated, primarily nonmarine tongues of the Horseshoe Canyon Formation display a reciprocal relationship, thinning from the west-northwest toward the marine realm of the east-southeast. In addition, upward within the Horseshoe Canyon, there is a slight, but progressive, shift in isopach trends to thinning from west to east.

A total of 575 paleocurrent measurements were collected, primarily from thick channel sandstone bodies, from the 39 outcrops of the Horseshoe Canyon Formation measured. These include trough-crossbedding (txb), ripple crosslamination (rxl), channel trends, inclined heterolithic stratification (IHS), inclined bedding stratification (IBS), and lateral accretion surfaces (LA). Paleocurrent evidence from these thick fluvial and tidally influenced channel sandstones occur either as *direct indicators* (txb, rxl, channel trends), which are a direct result of in-channel, sediment-carrying flow and whose dip direction defines the flow direction, or as *indirect indicators* (IHS, IBS, LA surfaces), which are a result of lateral accretion at channel margins, accumulated on surfaces oriented at approximate right angles to local channel flow direction. Once the clear paleoflow direction of channels within a unit is established by plotting a significant number of direct indicators, then the indirect indicators can be used to support that interpreted dominant channel trend (because they suggest a flow direction at 90° to their original orientation), using the resultant vector of the direct indicators as a guide.

Horseshoe Canyon Formation. A total of 446 direct paleoflow indicators (360 txb, 85 rxl, 4 channel trends) from 39 outcrops, presents a clear generalized paleoflow direction with a mean vector of approximately 110° (Fig. 75a). Additionally, 133 indirect paleoflow indicators (59 IHS, 41 IBS, 33 LA surfaces) from 39 outcrops, suggest a variable dispersal direction with a mean toward approximately 80° (Fig. 75b). My interpretation of these data is that for the Horseshoe Canyon Formation depositional system in south-central Alberta, the general sediment dispersal direction was to the east-southeast at about 100–110°. This direction is toward the known Bearpaw marine basin, and suggests a general shoreline trend of north-northeast–south-southwest. These interpretations are similar to conclusions reached for these strata by Rahmani (1983) and Nurkowski and Rahmani (1984) in the Plains, and Jerzykiewicz and Labonte (1991) in the central Foothills, using smaller data sets.

Hoodoo tongue. A total of 92 direct paleoflow indicators (80 txb, 10 rxl, 2 channel trends) from eight outcrops, presents a clear paleoflow direction with a mean vector of approximately 115° (Fig. 76a). Additionally, 56 indirect paleoflow indicators (28 IHS, 21 IBS, 7 LA surfaces) from eight outcrops, suggest a variable dispersal direction with a mean toward approximately 90° (Fig. 76b). My interpretation of these data is that for the tidally influenced channels of the lower Horseshoe Canyon Formationin the study area, near the marine-shoreline transition, the sediment dispersal direction was to the southeast at about 100–110°. This direction is toward the known Bearpaw marine basin, and suggests an associated general shoreline trend of north-northeast–south-southwest.

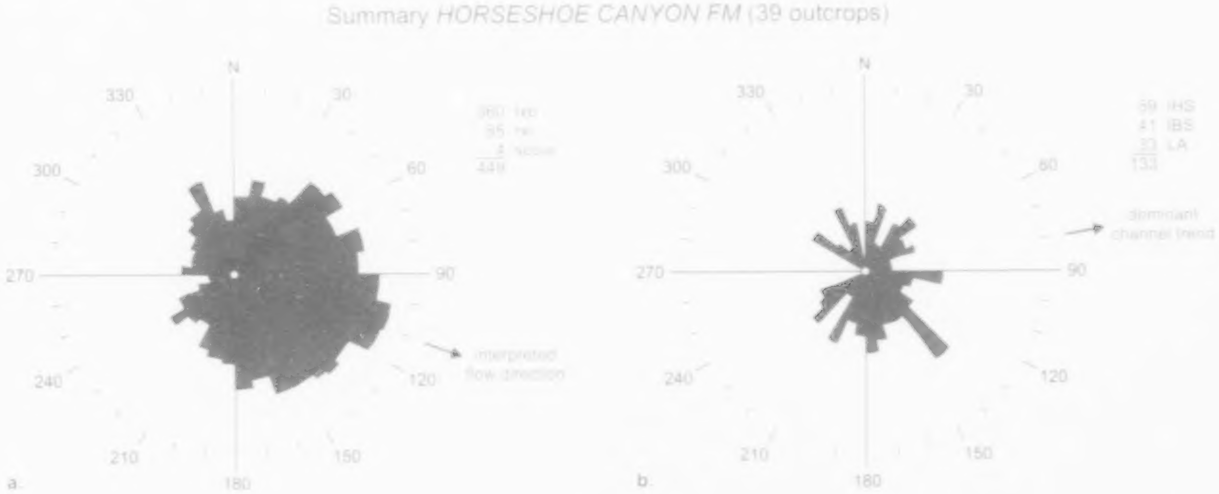

Summary *HORSESHOE CANYON FM* (39 outcrops)

Figure 75. *a) Total Horseshoe Canyon Formation direct paleoflow indicators (sedimentary structures that are direct indicators of flow direction), and resultant flow direction. b) Total Horseshoe Canyon Formation indirect paleoflow indicators (depositional surfaces that dip laterally into channels), and resultant fluvial channel flow direction.*

Midland tongue. A total of 159 direct paleoflow indicators (141 txb, 16 rxl, 1 channel trend, 1 parting lineation) from 19 outcrops, presents a clear paleoflow direction with a mean vector of approximately 115° (Fig. 77a). Additionally, 45 indirect paleoflow indicators (21 IHS, 15 IBS, 19 LA surfaces) from 19 outcrops, suggest a variable dispersal direction with a mean toward approximately 80° (Fig. 77b). I interpret these data, for the fluvial and minor tidally influenced channels of the middle Horseshoe Canyon Formation in the study area, near the marine-shoreline transition, to indicate that the sediment dispersal direction was to the east-southeast at about 100–110°. This direction is toward the known Bearpaw marine basin and associated shoreline trend of north-northeast–south-southwest.

Tolman tongue. A total of 94 direct paleoflow indicators (52 txb, 42 rxl), from 16 outcrops, presents a clear paleoflow direction with a mean vector of approximately 115° (Fig 78a). Additionally, 13 indirect paleoflow indicators (8 IHS, 2 IBS, 3 LA surfaces), from seven outcrops (although a minimal sample), suggest a variable dispersal

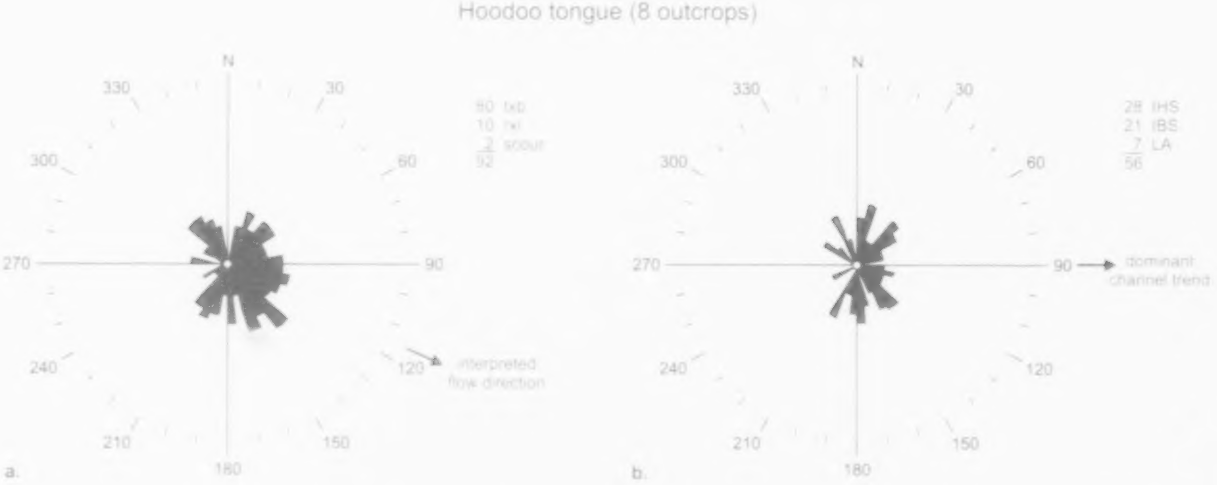

Hoodoo tongue (8 outcrops)

Figure 76. *a) Total Hoodoo tongue direct paleoflow indicators (sedimentary structures that are direct indicators of flow direction), and resultant flow direction. b) Total Hoodoo tongue indirect paleoflow indicators (depositional surfaces that dip laterally into channels), and resultant fluvial channel-flow direction.*

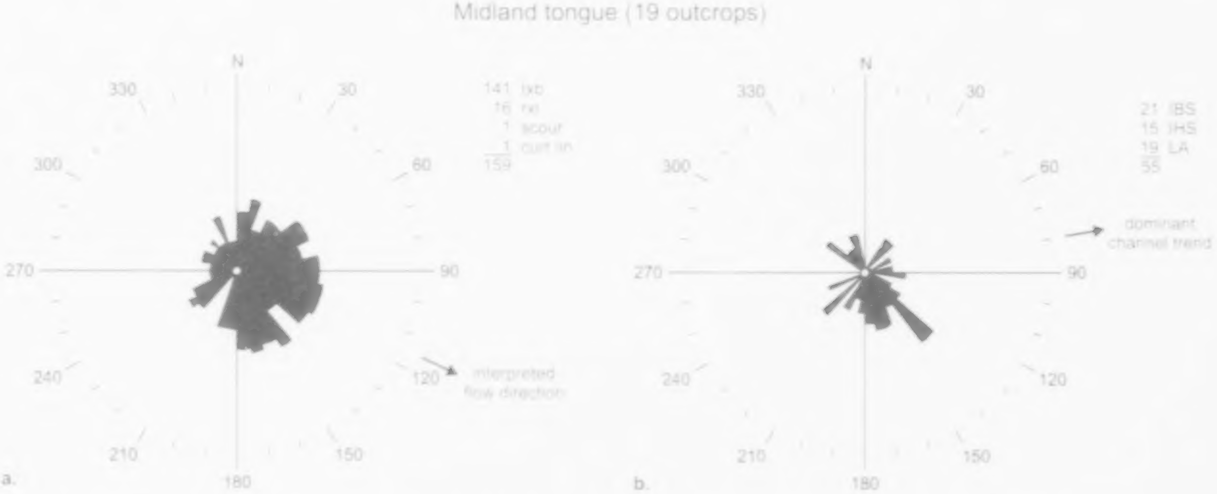

Midland tongue (19 outcrops)

Figure 77. *a) Total Midland tongue direct paleoflow indicators (sedimentary structures that are direct indicators of flow direction), and resultant flow direction. b) Total Midland tongue indirect paleoflow indicators (depositional surfaces that dip laterally into channels), and resultant fluvial channel-flow direction.*

direction with a mean toward approximately 100° (Fig. 78b). My interpretation of these data is that for the fluvial channels of the upper, non-coaly Horseshoe Canyon Formation in the study area, far from the marine-shoreline transition, the sediment dispersal direction was to the east-southeast at about 110°. This direction is toward the known Bearpaw marine basin.

Carbon tongue. A total of 104 direct paleoflow indicators (87 txb, 17 rxl), from ten outcrops (although a minimal sample), presents a clear paleoflow direction with a mean vector of approximately 95° (Fig. 79a). Additionally, nine indirect paleoflow indicators (2 IHS, 3 IBS, 4 LA surfaces), from four outcrops, suggest a variable dispersal direction with a mean toward approximately 90° (Fig. 79b). My interpretation of these data is that for the fluvial channels of the upper coaly Horseshoe Canyon Formation in the study area, far from the marine-shoreline transition, the sediment dispersal direction was to the east at 90–95°.

From the foregoing discussion, I suggest that there was a minor shift in sediment dispersal direction, from paleoflow toward 115° (east-southeast) to paleoflow toward 90° (east)

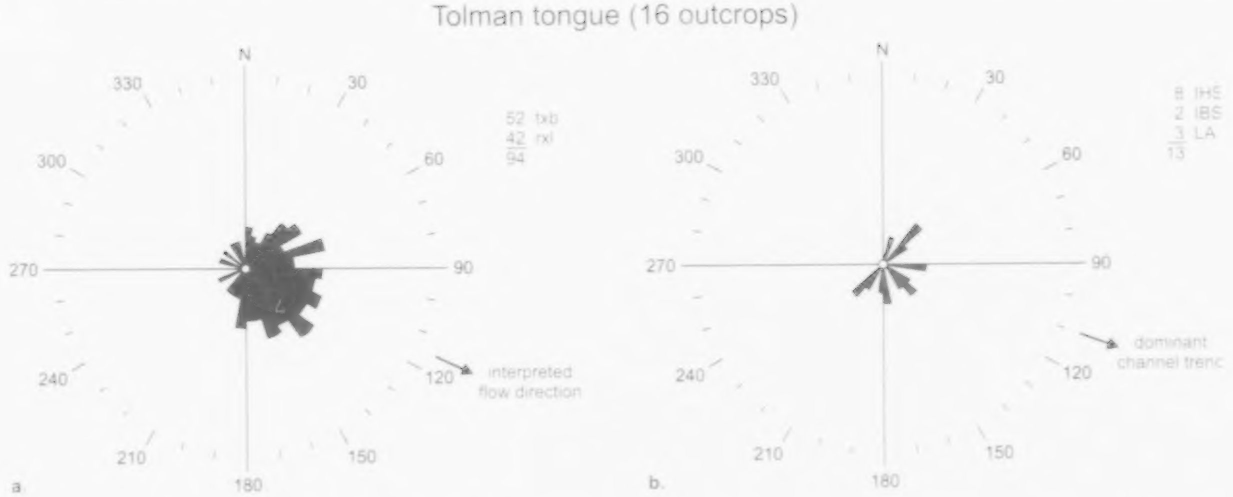


***Figure 78.** a) Total Tolman tongue direct paleoflow indicators (sedimentary structures that are direct indicators of flow direction), and resultant flow direction. b) Total Tolman tongue indirect paleoflow indicators (depositional surfaces that dip laterally into channels), and resultant fluvial channel-flow direction.*

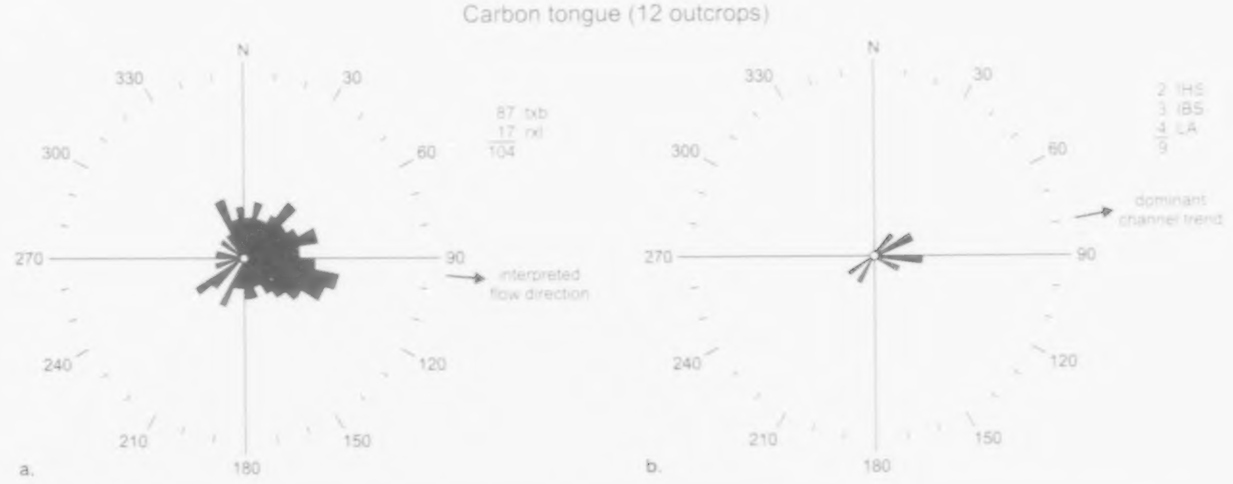


***Figure 79.** a) Total Carbon tongue direct paleoflow indicators (sedimentary structures that are direct indicators of flow direction), and resultant flow direction. b) Total Carbon tongue indirect paleoflow indicators (depositional surfaces that dip laterally into channels), and resultant fluvial channel-flow direction.*

during the time of deposition of the upper Horseshoe Canyon Formation (Carbon tongue). This trend continues into the overlying lower Scollard-Coalspur formation channel sandstone deposits, with paleoflow to the east-northeast or northeast (Jerzykiewicz and Labonté, 1991; my own data on measured sections in this report).

STRATIGRAPHIC ARCHITECTURE: BEARPAW-HORSESHOE CANYON CYCLES

3-D geometrical framework

Although outcrops are extensive along several river valleys in central Alberta, these actually cover only a small proportion of the total geographic distribution of the Horseshoe Canyon Formation, and so the subsurface cross-sections are crucial to the understanding of the vertical and lateral regional framework of the unit. Subsurface study of the formation is assisted by the presence of regionally recognizable characteristics of its well log signature. Figure 80 illustrates the internal stratigraphic breakdown of the Horseshoe Canyon Formation, including the new sandy-coaly tongues, the intertonguing of Bearpaw marine units, and the interpreted stratigraphic framework. The five, new, nonmarine tongues designated in this report are clearly discernible from log signatures, which correlate to distinctive outcrop lithofacies assemblages, and which intertongue with the Bearpaw Formation marine shale units. In the present study, the recognition and correlation of the marine tongues that subdivide the predominantly continental Horseshoe Canyon Formation, their proximal extension back into the nonmarine clastic wedge, and their distinct association with coal zones, were fundamental factors in understanding the upper Campanian-Maastrichtian strata of south-central Alberta. The gamma ray-porosity log cross-sections included in this study use the regionally recognizable top of the Belly River Group

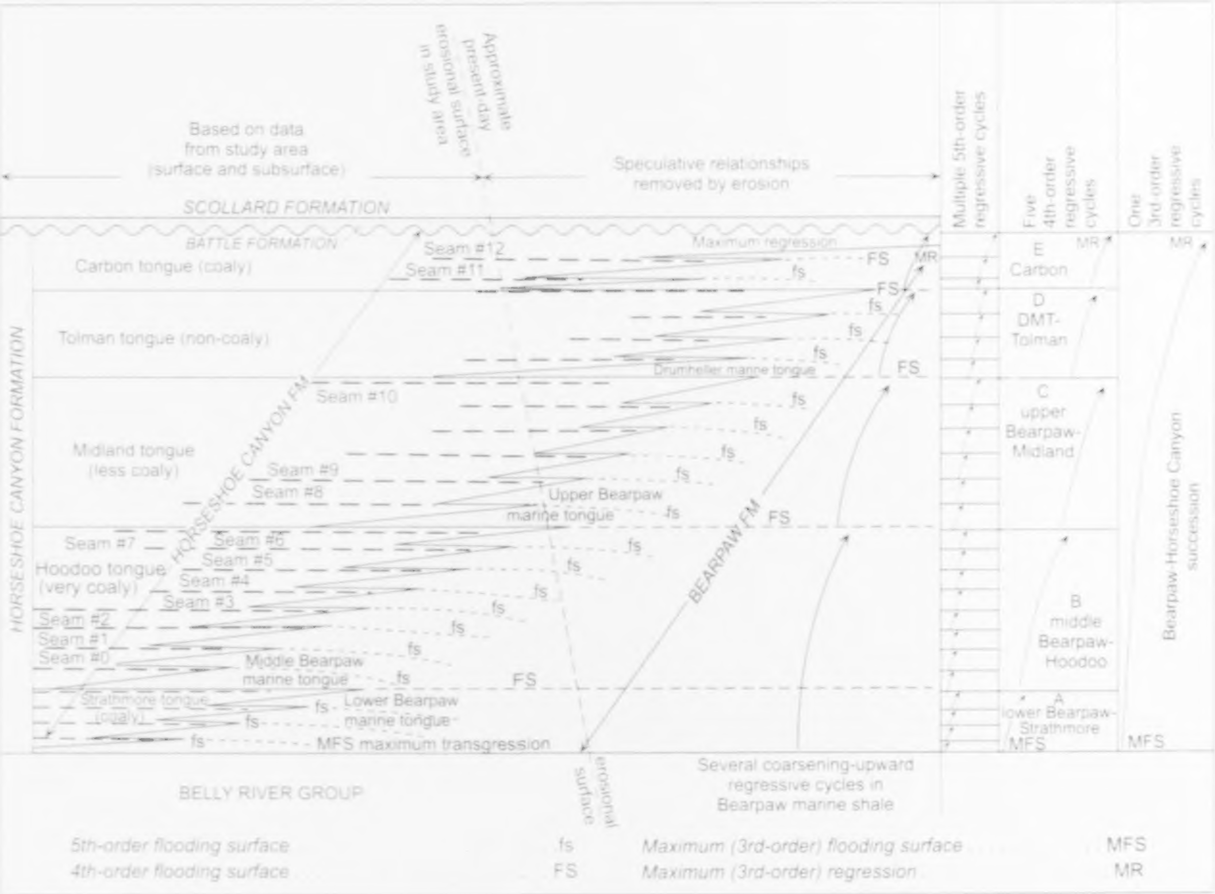


Figure 80. Schematic conceptual northwest-southeast cross-section of Bearpaw Formation-Horseshoe Canyon Formation depositional system, illustrating stratigraphic architecture and interpretive framework, and relation of coal seams to multiple transgressions in south-central Alberta.

(Lethbridge Coal Zone) as a datum. This datum marks the base of the Bearpaw Cycle of Weimer (1960) and is an important regional flooding surface throughout the southern Plains.

In the search for some consistent, and practically applicable, internal organization to the Bearpaw-Horseshoe Canyon succession, an empirical subdivision based on the presence of four correlatable marine shale tongues and the converse presence, absence, or abundance of five, nonmarine sandstone or coal tongues became apparent. These tongues are interbedded on a regional scale, with inverse thickness relationships. Although this kind of relationship has been illustrated for fifth-order subunits on a local outcrop scale for the limited portion of the strata exposed at Willow Creek, this is the first documentation of this fundamental, three-dimensional framework at the vertical and horizontal scale of the entire succession. Each nonmarine tongue thins and becomes more shaly to the southeast, as it gradually passes laterally into the equivalent portion of the Bearpaw marine shale. Conversely, each marine tongue thins and passes laterally into sandy-coaly deposits to the northwest. As the lowest Bearpaw marine tongue, resting on the Belly River Group, is the most extensive, and each successive flooding surface penetrated less far northwestward, it is clear that the overall southeastward thinning of the Horseshoe Canyon Formation is due to the diachronous, but noncontinuous, younging of the base of the Formation. It is also clear that the Horseshoe Canyon Formation represents an overall regressive systems tract composed of stacked transgressive-regressive cycles.

The tongues identified in this study are components of essentially coarsening-upward, asymmetrical, transgressive-regressive (T-R) fourth-order cycles, passing upward from shale-dominated to sandstone- and coal-dominated facies. Each typically comprises a lower, thinner, marine shale-dominated portion (Bearpaw tongue) and an upper, thicker, nonmarine sandstone- and coal-dominated portion (Horseshoe Canyon tongue). They clearly have regional lateral extents of hundreds of kilometres. Lower, marine, shaly portions rest abruptly on previous cycles and thicken to the south and east (basinward), whereas upper, sandy, primarily fluvial and shoreline-related portions thicken to the north and west (sourceward). In the southeastern portion of the area, where marine and nonmarine strata intertongue, basal boundaries of cycles are typically sharp, and placed at a flooding surface where marine shale overlies coal. These fourth-order T-R cycles are described in more detail below.

In this study, T-R cycles are not rigorously defined according to present genetic sequence stratigraphic schemes and delineating surfaces. However, in a set of strata where outcrops are concentrated in a certain area only, core data are rare, and subsurface log signatures represent an important data set, a pragmatic and utilitarian approach is suitable for initial subdivision. Thus, T-R cycle boundaries were defined at the bases of shaly tongues – tops of mappable sandy-coaly successions. Therefore, although the cycles are primarily characterized by regressive successions, they may include some transgressive strata at the top; more detailed study (as has been attempted at Willow Creek) is required to delineate the locations of actual transgressive surfaces within interbedded sandstone-siltstone-coal facies and establish a sequence stratigraphy. I sincerely hope that studies of this nature will be forthcoming. However, in the meantime, the present study attempts to focus attention on potential reservoir and aquifer trends and the limits of depositional systems.

Clearly, the locus of shoreline-related sandy deposition, and the penetration of marine influence, shifted southeastward across southern Alberta during the time of Bearpaw-Horseshoe Canyon Formation deposition. The deposition of each successive forestepping cycle displays a geographic shift of 20 to 50 km. Additionally, within the depositional area for each unit, there are areas of greater and lesser thickness, suggesting mappable points of sediment dispersal. It is clear that each cycle thins and becomes more shaly to the southeast, as it gradually passes laterally into the equivalent portion of the Bearpaw Formation marine shale. The basinward pinchout of each succeeding cycle overlies and is located southeastward of the preceding one. The overall southeastward thinning of the sandy clastic wedge is due to the diachronous younging of the base of the Horseshoe Canyon. In the Cypress Hills, the entire Horseshoe Canyon Formation-equivalent is less than 50 m thick and sandy facies are confined to the Eastend and Whitemud formations, which are here interpreted to correlate approximately with the Carbon tongue of the Horseshoe Canyon Formation.

It is also clear that each fourth-order cycle is actually a composite of several thinner, individual, generally coarsening-upward, asymmetrical fifth-order subunits that mimic the eastward thinning, fining and downlap trends of the larger sequences. Although some correlations are included on individual cross-sections, I made no concerted attempt in this study to correlate in three dimensions, map or formally define these individual fifth-order subunits. Some of these same subunits were identified as "coarsening-upward successions", especially in the "Drumheller coal zone" (or Hoodoo tongue) by McCabe et al. (1989). They obviously have more localized extents but are important because they likely comprise separate mappable channel- and shoreline-related reservoir and aquifer trends. However, the important work of Rahmani (1983), Saunders (1989), Ainsworth (1994) and Lavigne (1999) in the East Coulee and Willow Creek areas documented the internal complexities within a single fourth-order T-R cycle, as defined here, and serves as a model for further work in play definition. These authors identified several northeast-southwest-trending progradational shoreline subunits (approximately fifth-order), separated by marine flooding surfaces, all contained within the Hoodoo tongue. Each subunit passes laterally to the northwest into nonmarine interbedded sandstone, siltstone and coal making up the bulk of the Horseshoe Canyon Formation. In addition, Rahmani (1983) and Ainsworth (1994) identified incised fluvial and estuarine systems trending northwest-southeast.

Cycle A (lower Bearpaw-Strathmore: maximum transgression)

The lower Bearpaw tongue represents a rapid, extensive emplacement of marine strata over the relatively flat upper surface of the Dinosaur Park Formation (Belly River Group) strata. This incursion extended north and west to a zero pinch-out line between Calgary and Red Deer in this study area. The resulting thin marine shale unit (including part of the transgressive systems tract, or TST, the maximum transgression surface and the lower regressive systems tract, or RST) at the base of the Bearpaw-Horseshoe Canyon succession represents the maximum transgression recorded: later Bearpaw tongues were generally less extensive (Fig. 81a). In the far southeastern part of the study area, stratigraphic continuity of this tongue with the main body of the Bearpaw Formation can be demonstrated in subsurface data. In most of the study area (except the far southeast), the lower Bearpaw tongue passes gradationally upward into Strathmore tongue shoreline-nonmarine sandstone-siltstone-coal, representing the bulk of the generally coarsening-upward regressive systems tract (RST).

Toward the south and east, the Strathmore sandy wedge thins, and becomes more shaly, pinching out from the base as it passes laterally into the upper portion of the lower Bearpaw tongue. The zero edge of the Strathmore tongue follows an irregular, lobate, northeast-southwest-trending line from Gleichen to Sullivan Lake, pinching out in the subsurface beneath the village of Strathmore, before equivalent marine strata climb to surface exposures along the Red Deer River. Thus, the sandy East Coulee lithofacies are never exposed in outcrop in this area. Multiple individual coarsening-upward cycles at a fifth-order scale are present. The lobate geometry depicted on the Strathmore isopach map (and on the inverse-image on the underlying lower Bearpaw tongue map) indicates multiple linear points of greater sandy sediment input. These are located in the Red Deer, Three Hills, Carbon and Strathmore areas, with west-northwest–east-southeast trends. Fourth-order Cycle A represents the initial Bearpaw marine incursion from the southeast into post-Belly River central Alberta, and the subsequent regression of the sandy shoreline as sediment input exceeded base level rise.

Cycle B (middle Bearpaw–Hoodoo)

The middle Bearpaw tongue represents a rapid, extensive emplacement of marine sediments over the relatively flat upper surface of the Strathmore tongue strata, which extended north and west to a zero pinch-out line between Calgary and the eastern Red Deer area in the study area. This thin marine shale unit (including part of the transgressive systems tract, or TST, the maximum transgression surface for this sequence and the lower regressive systems tract, or RST) is somewhat less extensive than the lower Bearpaw tongue, but more extensive than later Bearpaw tongues. In the far southeastern part of the study area, stratigraphic continuity with the main body of the Bearpaw Formation can be demonstrated in subsurface data. Throughout the study area, the middle Bearpaw tongue passes gradationally upward into Hoodoo tongue shoreline and nonmarine strata composed of sandstone, siltstone, and coal, representing the bulk of the generally coarsening-upward RST.

Toward the south and east, the Hoodoo sandy wedge thins, and becomes more shaly, pinching out from the base in an offlapping geometry as it passes laterally into the upper portion of the middle Bearpaw tongue. The zero edge of the Hoodoo follows an irregular lobate north-south-trending line in the Hanna area, just at the eastern edge of the subsurface data set, but the Hoodoo tongue is present in surface exposures, including the well-studied outcrops at Willow Creek. Here, multiple individual coarsening-upward cycles at a fifth-order scale are present. The lobate geometry depicted on the Hoodoo isopach map (and on the inverse-image on the underlying middle Bearpaw tongue map) indicates multiple linear points of greater sandy sediment input. These are located in the Lacombe, Innisfail, Three Hills, Beiseker and Strathmore areas, with west-northwest–east-southeast trends. Fourth-order Cycle B represents a lesser, renewed transgression of Bearpaw marine conditions, and subsequent more extensive regression of sandy shoreline deposits as nonmarine conditions began to dominate in central Alberta.

Cycle C (upper Bearpaw-Midland)

The upper Bearpaw tongue represents a rapid, extensive transgression over the relatively flat upper surface of the Hoodoo tongue strata, which extended westward to a zero pinch-out limit between Strathmore and Alix. In the study area, this thin marine shale unit (including part of the transgressive systems tract, or TST, the maximum transgression surface for this sequence and the lower regressive systems tract, or RST) is thinner and less extensive than the middle Bearpaw tongue, and covers only the eastern half of the study area. The subsurface data set does not extend quite far enough eastward to unequivocally demonstrate continuity with the Bearpaw Formation, but this is assumed. Where present, the upper Bearpaw tongue passes gradationally upward into Midland tongue shoreline and nonmarine sandstone, siltstone, and coal, which represents the bulk of the coarsening-upward RST.

Toward the south and east, the very thick Midland sandy wedge thins, and becomes more shaly, pinching out from the base in an offlapping geometry as it passes laterally into the upper portion of the upper Bearpaw tongue. However, the zero edge of the Midland is clearly far to the east and southeast of this study area and therefore would not be traceable in surface exposures or subsurface data in this region of Alberta. Multiple individual coarsening-upward cycles at a fifth-order scale are present in the easternmost wells. The lobate geometry depicted on the Midland isopach map (and on the inverse-image on the underlying upper Bearpaw tongue map) indicates multiple linear points of greater sandy sediment input. These are located in the Innisfail, Three Hills, Beiseker, and Strathmore areas, with west-east trends. Fourth-order Cycle C represents a far less extensive re-transgression of Bearpaw marine conditions, and subsequent much more extensive regression of sandy shoreline deposits as nonmarine conditions became fully dominant in central Alberta, and essentially lasted for the rest of the geological record. The lesser presence of coal and the slightly better development of calcisols, compared to the underlying Hoodoo tongue, suggests a slightly more arid climate.

Cycle D (DMT-Tolman)

The Drumheller marine tongue (actually, a further upper Bearpaw tongue, although stratigraphic continuity with the Bearpaw cannot be demonstrated in this study area because of a lack of surface or subsurface data to the east) represents a rapid transgression over the upper surface of the Midland tongue strata at about the time of the Campanian–Maastrichtian boundary. This incursion extended northward and westward to a zero pinch-out line between Strathmore and Carbon. This thin (0–20 m) marine shale unit (including part of the transgressive systems tract, or TST, the maximum transgression surface for this sequence and the lower regressive systems tract, or RST) is thinner and less extensive than the upper Bearpaw tongue, and covers only the southeastern quarter of the study area. Where present in outcrops and subsurface wells of the far southeast, it passes gradationally upward into Tolman tongue nonmarine (primarily pedogenic) siltstone and sandstone, which represents the bulk of the RST. The subsurface and outcrop data sets are insufficient to reveal the presence of fifth-order cycles.

Because of its distinctive heavily burrowed oyster shell-rich facies, within a predominantly coal-rich nonmarine succession, the DMT has garnered geologists' attention as a unique and somewhat mysterious manifestation. The observations of this study suggest that it is simply one of four (or more) regionally important, but not unique, marine tongues which subdivide the Horseshoe Canyon Formation. Only by directly incorporating subsurface data into study of outcrops of the entire clastic wedge (both for the first time) can we now understand the DMT's true position in the upper Campanian–Maastrichtian strata of central Alberta. In addition, the unique presence at the Bleriot Ferry section of a few scattered, large oyster shells at a higher level in the Tolman tongue suggests that there may originally have been more marine tongues, yet unidentified, with significant regional extents. It is likely that similar oyster shell bar facies are associated with the landward pinchout points of each of the regional marine tongues, but by coincidence, the DMT is the only one which pinches out in a well-traveled area of excellent outcrops.

Toward the east, the thick Tolman silty-sandy wedge thins. However, the zero edge of the Tolman is clearly far to the east or southeast of this study area (in the zone where upper Campanian–Maastrichtian strata are lost to erosion) and therefore would not be traceable in surface exposures or subsurface data in this region of Alberta. The facies, geometry and relations to under- and overlying cycles indicate that the Tolman tongue represents a very extensive regression in the Horseshoe Canyon Formation. Interestingly, the Tolman lithologies, depositional style and lack of coal are reminiscent of the St. Mary River Formation of southwestern Alberta (Hamblin, 1998b, 1998d), and may represent a northern expression of that lithofacies association. The lobate geometry depicted on the Tolman isopach map indicates multiple linear points of greater sandy sediment input. These are located in the Red Deer, Three Hills, Irricana, and Strathmore areas, with west-east trends. Fourth-order Cycle D represents a regional, but attenuated, re-transgression of Bearpaw marine conditions into this study area, and subsequent very extensive regression of thoroughly pedogenically altered silty, sandy, floodplain deposits as nonmarine conditions were completely and permanently established in central Alberta for the rest of the geological record. The lack of coal, complete dominance of vertisols and extensive development of calcisols (especially toward the top) are interpreted to indicate that the Tolman tongue represents the most arid climatic state in the Horseshoe Canyon Formation.

Cycle E (Carbon; maximum regression)

Unlike the previous cycles, there is no identifiable basal marine tongue associated with the Carbon tongue in the study area. There is no physical way to document the existence of such a unit at this point in the stratigraphy outside the study area, farther to the east or southeast, because there is a lack of surface and subsurface data. However, such a marine tongue may exist and be recorded far to the southeast (refer to discussion below). If a zero edge of the Carbon exists, it is clearly far to the east and southeast of this study area and therefore would not be traceable in surface exposures or subsurface data in this study area.

The Carbon lithologies represent a return to the depositional style reminiscent of the earlier Hoodoo and Midland tongues, and suggest development of thick coaly deposits in a more humid climate than that interpreted for the underlying Tolman tongue. The lobate geometry depicted on the Carbon isopach map (although data is confined only to the western portion of the study area) suggests multiple linear points of greater sandy sediment input. These are located in the Red Deer, Innisfail, Carbon, and Calgary areas, with west-east or west-southwest–east-northeast trends. Fourth-order Cycle E may have included an attenuated tongue of Bearpaw marine strata to the east and southeast of this study area (no longer preserved), but certainly represents an extensive regression of sandy-coaly deposits as nonmarine conditions continued to dominate in central Alberta. The upper portion of Cycle E is represented by the commonly present Whitemud sandstone, which has the characteristics of a rooted, ganister-like paleosol horizon developed in a low-relief, waterlogged, delta-plain setting. This is interpreted as the albic horizon of an intensely developed spodosol associated with the regional subaerial unconformity that separates the Whitemud from the overlying Battle and Scollard formations. An eluviated, leached horizon of this nature represents prolonged subaerial exposure, perhaps for up to thousands of years. Thus, this subaerial unconformity represents the maximum regression surface for the entire Dinosaur Park-Bearpaw-Horseshoe Canyon third-order sequence (Fig. 81b), and the upper sequence boundary.

The unconformably overlying organic-rich, ash-rich Battle Formation with well-preserved tuff horizons may represent a regionally expressed lacustrine deposit associated with the Scollard depositional system, also related to a setting where subsidence temporarily overwhelmed sediment supply. The unique Battle Formation lacustrine (or even brackish marine) mudstone may actually signal an additional unrecognized marine transgression at the base of the Scollard Formation.

Correlation with distal marine sequences

The presence of stacked coarsening-upward sequences in the more distal marine Bearpaw Formation, similar to the fourth-order cycles described here, has also been noted in the past. The five shale and sandstone members of the Bearpaw Formation (and overlying basal Horseshoe Canyon) identified by Givens and Wall (1971) in central Alberta actually seem to represent three coarsening-upward regressive sequences: 1) lower shale-second Castor sandstone (total 80 m thick), 2) middle shale-first Castor sandstone (total 45 m thick), and 3) upper shale-basal Horseshoe Canyon (total 35 m thick). These may correlate directly to several of the cycles identified in this study.

The six offlapping regressive, coarsening-upward cycles of the Bearpaw and basal Horseshoe Canyon formations identified in a similar study area by Habib (1981) indicate a very similar depositional motif throughout the post Belly River–pre-Scollard late Campanian–Maastrichtian interval. The cycles of Habib (1981) correlate in various ways to the

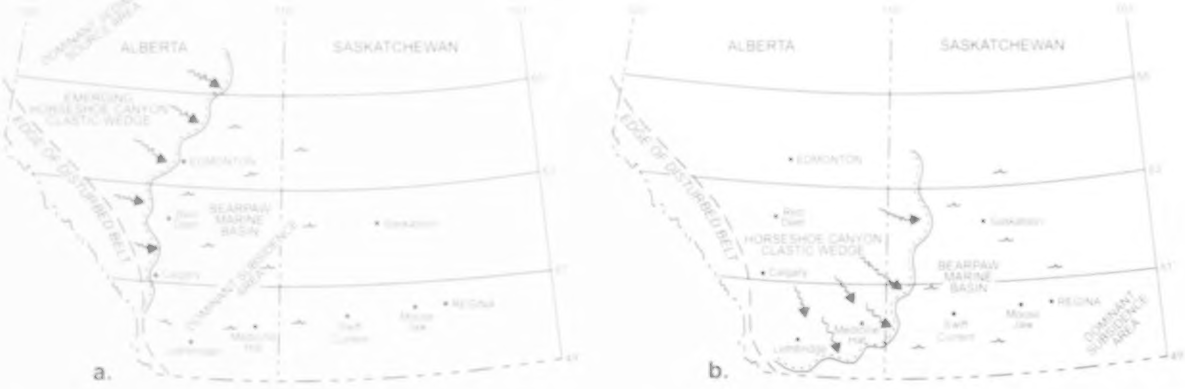


Figure 81. *Paleogeography during the time of Bearpaw-Horseshoe Canyon Formation deposition. a) Maximum Bearpaw transgression (lower Bearpaw tongue, Cycle A), and b) maximum Horseshoe Canyon regression (Carbon tongue, Cycle E).*

fourth- and fifth-order sequences identified in this study. For example, Cycle A of Habib (1981) is approximately correlative to the distal equivalent of my fourth-order Cycle A, whereas his Cycle C is approximately equivalent to a fifth-order subunit within my Cycle B. Likewise Cateneanu et al. (2000) identified a series of T-R sequences, on a scale of 10–20 m thick, in the Bearpaw Formation of southern Alberta (approximately equivalent to fifth-order cycles in this study).

In similar fashion, the five members of the Bearpaw described by Lines (1963) in the Cypress Hills, plus the overlying sandy formations, actually represent three major coarsening-upward sequences, although that author did not recognize these. These are 1) Manyberries-Oxarart (total 236 m thick, and the bulk of the Bearpaw), 2) Belanger-Thelma (total 33 m thick), and 3) Medicine Lodge-Eastend/Whitemud (total 60 m thick). These, in fact, likely represent more basinward equivalents of several of the fourth-order cycles described here, although they are separated from my study area by 250 km of non-preservation of these strata.

Lerbekmo and Braman (2002) made detailed magneto- and biostratigraphic correlations of the upper Campanian–Maastrichtian succession, between Red Deer River and Cypress Hills, which can be compared to the cycles defined in this study. From their careful work, several relevant conclusions are clear: 1) the thick, shaly Manyberries Member of the Bearpaw Formation in Cypress Hills occupies the portion of the Red Deer River section equivalent to the lower Bearpaw tongue, the East Coulee tongue, the middle Bearpaw tongue, and the Hoodoo tongue of this study (Cycles A, B) and these units are all late Campanian in age; 2) the Oxarart and Belanger sandy members of the Cypress Hills are approximately equivalent to the Midland tongue of this study (Cycle C), beneath the level of the Drumheller marine tongue, and are all of late Campanian age; 3) the sandy Thelma Member of Cypress Hills is likely equivalent to the Tolman tongue of this study (Cycle D), and both are of Maastrichtian age; and 4) the Medicine Lodge shale-Eastend/Whitemud sandstone succession in Cypress Hills is essentially equivalent to the Carbon tongue of this study (Cycle E), and these units are of Maastrichtian age (see Lerbekmo and Braman, 2002, their Fig. 14). These detailed correlations also support the interpretation that the upper part of the Carbon-Eastend sandy units (Cycle E) represent the maximum regression point in the Dinosaur Park-Bearpaw-Horseshoe Canyon third-order sequence, capped by the Whitemud regionally developed spodosol horizon and the sub-Battle regional subaerial unconformity.

The cyclothems identified in equivalent coarser grained strata in the central Foothills to the northwest (sourceward) of the study area by Jerzykiewicz (1985), may also correlate to my fourth-order coarsening-upward cycles.

Obviously, further regional stratigraphic study, melding surface and subsurface data in the style attempted here, is required to correlate fully and synthesize the previous work on the Bearpaw sequences with the now identifiable framework for the Horseshoe Canyon Formation. This would allow construction of a consistent tectonostratigraphic model and better interpretation of the late Campanian–Maastrichtian of southern Alberta in order to fully appreciate and exploit the regional possibilities and resource potential.

REGIONAL FRAMEWORK AND TECTONIC FACTORS

Tectonic controls

In the central Plains of Alberta the Horseshoe Canyon Formation represents the southeastward, noncontinuous regression of the Bearpaw sea as a synchronous, vast fluvial, estuarine and shoreline depositional system spread from the north and northwest into the Bearpaw marine basin. The bulk of the formation is interpreted to represent strata accumulated during repeated phases of increased accommodation. The base of this formation becomes diachronously younger to the east and southeast by intertonguing of nonmarine shoreline facies and Bearpaw Formation shallow-marine facies, in an arrangement related to the stacking of shorelines into the basin, as described above.

The schematic west-east cross-section (Fig. 80) is a simplified pictorial summary of the geometric and depositional relationships indicated above. Although greatly expanded in vertical exaggeration, the geometries shown are internally consistent and match those developed from the cross-sections and maps discussed previously. It depicts the vertical stacking of the new informal lithostratigraphic units identified in this study and the regionally correlatable fourth-order regressive cycles described above. The current surface erosional level has removed all data to the east and southeast of the study area, out to the location of the Cypress Hills.

In general, the predominant processes that control shoreline position and stratigraphic patterns are the rate of change of sediment accommodation vs. the rate of sediment supply. The Horseshoe Canyon Formation clearly represents a long-term trend of sediment supply overwhelming basin subsidence and accommodation space, allowing the southeastward progradation of the clastic wedge, which extended over hundreds of kilometres and continued for about 7 Ma. Development of a prograding depositional system of this magnitude, with consistent character, suggests a fundamental regional, probably tectonic, control on the interaction of basin subsidence in the southeast and sediment supply from the northwest.

The two-phase stratigraphic model of foreland basin sequences proposed by Heller et al. (1988) predicts that episodes of thrust-load emplacement, causing rapid proximal subsidence (base level rise), should generate fine-grained deposits over most of the basin (and possible transgression: underfill phase), whereas subsequent periods of tectonic quiescence, allowing erosional removal of the load and flexural rebound (base level fall), should generate widespread coarser sheet deposits over most of the basin (and general regression: overfill phase). This conceptual framework may be applicable to the Horseshoe Canyon Formation in southern Alberta.

Eberth and Hamblin (1993) and Hamblin (1997b) discussed the tectonic establishment of a southeasterly tilt in the WCSB as a primary influence on the emergence of the Dinosaur Park Formation (upper Belly River) depositional system (the TST of this third-order T-R sequence) from the northwest. Apparently this basinal configuration also persisted throughout deposition of the Bearpaw Formation and Horseshoe Canyon Formation (the RST of this third-order T-R sequence) in the central Alberta Plains. The overall transgressive trend of the Dinosaur Park-lowest Bearpaw complex represented a trend of increasing basin subsidence in the southeast progressively overwhelming sediment supply from the northwest (Hamblin, 1997a, b). This increase in subsidence rate allowed Bearpaw transgression to proceed from the southeast toward the northwest into south-central Alberta, manifest as the lower Bearpaw tongue, which contains the maximum flooding surface just above the top of the Dinosaur Park Formation (subsidence > sediment supply). This latter tectonic trend of increased subsidence was clearly reversed as the Horseshoe Canyon Formation depositional system invaded the Bearpaw sea from the northwest into southern Alberta, and extensive noncontinuous progradation of the fluvial-shoreline facies assemblages toward the southeast was re-established (sediment supply > subsidence).

In comparison to the earlier Foremost Formation of the Belly River Group (see Hamblin and Abrahamson, 1996), the Horseshoe Canyon Formation displays qualitatively similar styles and geometries but relatively more pronounced vertical stacking of cycles, rather than lateral offlapping, and much more abundant and thicker coal seams. These relationships suggest relatively more pronounced base level rise, probably due to more rapid basin subsidence associated with the late Campanian–Maastrichtian Bearpaw marine phase, as opposed to the Campanian Lea Park marine phase. A greater rate of subsidence in the presence of high sediment supply allows greater vertical aggradation. This suggests qualitatively similar, but relatively stronger, tectonic effects in the foreland in the late Campanian–Maastrichtian. In addition, the regional locus of subsidence was in southeastern Alberta, and sediment input was from a regional source to the northwest, indicating the basinal geometry had altered somewhat from the earlier Campanian third-order sequence as a result of a shift in tectonic effects.

Regional framework

The Horseshoe Canyon Formation represents a third-order, generally regressive nonmarine depositional system that thins from northwest to southeast from the base, as it passes basinward into marine shale of the Bearpaw Formation. It is important to note that the "base of the Horseshoe Canyon" is not a single stratigraphic horizon, as traditionally considered in the Red Deer River valley. It is actually a highly diachronous contact represented by multiple Bearpaw-Horseshoe Canyon transitions, depending on geographic location and stratigraphic position. At any given surface or subsurface locality, that marine shale to nonmarine sandstone and coal transition may be represented by the transition within any of the fourth- or fifth-order cycles identified in this study. Only reference to a regional framework such as that delineated here for the first time can pinpoint the stratigraphic level, and therefore the lateral correlations, appropriate to that well or outcrop.

Within this package, the fourth-order cycles A to E are primarily regressive successions (acknowledging the likely presence of some transgressive strata at the top of each) which represent the responses of the depositional system to the shorter-term interactions of sediment supply and basin subsidence. The regressive sand-dominated portions of the cycles (in fact, the new informal tongues identified within the Horseshoe Canyon Formation in this study) are mappable over thousands of square kilometres and also are probably related directly to tectonic control. The fourth-order coarsening-upward cycles are interpreted as shallowing-upward, marine-to-nonmarine transitional successions. In the southeastern part of the study area, where the marine tongues are present, each cycle begins with flooding characterized by marine shale-dominated deposition, upward increase of shallow-marine sandy deposits, and culminates in shoreline and floodplain sandstone-coal facies (Fig. 14, 15, 16, 80). There, basal boundaries of cycles are typically sharp, placed (for convenience and ease of recognition in the subsurface) where interpreted marine shale overlies a flooding surface at the top of coaly strata (recognizing that the upper coals of each cycle may be transgressive in nature), and are essentially coincident with the upper boundaries of the new, sand-dominated tongues identified. Toward the northwest, beyond the reach of the identifiable marine tongues, cycle boundaries are more cryptic, but are likely traceable for some distance into the fluvial depositional system.

Within the fourth-order tongues and cycles, geographically distinct thickness trends are present, interpreted as delineating sediment input points. Each cycle, therefore, is not laterally (regionally) homogeneous. Within each fourth- and fifth-order cycle, fluvial and estuarine channelized sandstone bodies should have west-northwest–east-southeast or west-east regional trends, and shorelines (positioned in lower parts of the newly defined members) should have northeast-southwest regional trends. Sediment input was predominantly from the west and northwest throughout the time of Horseshoe Canyon Formation deposition. Marine tongues of the Bearpaw Formation thicken to the east and southeast, indicating that this was the area of long-lived marine deposition. This area is therefore interpreted as the locus of long-term foreland basin subsidence and predominantly marine deposition during late Campanian–Maastrichtian time.

In fact, in the Cypress Hills area of southeastern Alberta, the comparable interval is entirely represented by the Eastend–Whitemud formations: a single 50 m sandy shoreline-related, coarsening-upward succession with marine shale at the base and coal at the top. This is interpreted here as a fourth-order cycle representing the maximum regression to the east and southeast during late Campanian–Maastrichtian time. These strata may correlate to the maximum regression phase Carbon Member of south-central Alberta identified in the present study, based on the magneto- and biostratigraphic evidence of Lerbekmo and Braman (2002). The coarsening-upward sequences known from the underlying Bearpaw Formation of Cypress Hills may correlate to other units identified in this study, as suggested above.

Within the marine portions of the fourth-order cycles (i.e., the Bearpaw tongues), individual fifth-order cycles bounded by localized flooding surfaces are present. These are indicated on the west-east cross-sections (Fig. 14, 15, 16) and depicted on the schematic diagram (Fig. 80). These downlap basinward and can be traced shoreward into thin, shoreline-related units at the bases of the primarily nonmarine regressive members of the Horseshoe Canyon Formation. Although these cycles offlap laterally in an overall progradational motif, they display much more vertical aggradation and stacking than comparable sequences of the Foremost Formation (Belly River Group). This effect, resulting from a greater overall rate of subsidence and base level rise relative to sediment supply, led to the much greater abundance and thickness of coal seams in Horseshoe Canyon vs. Belly River cycles.

These are the fifth-order units that have been so carefully studied in outcrop in the thin transition zone (base of Hoodoo tongue) exposed in the East Coulee-Willow Creek area. These previous studies illustrate the variations, complexities and different reservoir and aquifer styles present in these transitions. However, none of the other transition zones defined in this study have been previously recognized, studied or exploited. The shoreface depositional trends of these fifth-order progradational cycles could be mapped in detail as individual reservoir and aquifer bodies with identifiable northeast-southwest trends and limited extents. Channelized depositional forms, both fluvial and estuarine, which could act as additional individual reservoir or aquifer bodies with different northwest-southeast trends are also present and could be mapped in detail.

Coals and regional transgressions

Trends of coal thickness in the lower parts of the Horseshoe Canyon generally follow southwest-northeast directions (McCabe et al., 1989) approximately parallel to interpreted shoreline trends, and may be related to transgressive pressure as they are thickest and best developed just beneath marine flooding surfaces. In essence, the bases of the coals could represent the "turn-around points" from regressive to transgressive conditions. The strata that make up the coal zones are interpreted as aggradational floodplain sediments probably deposited as a result of the transgression that began deposition of the succeeding cycle, rather than as maximum regressive deposits. The southwest-northeast trends of coal thickness are interpreted to reflect the zone of maximum transgressive pressure and vertical aggradation associated with the marine tongue that overlies each fourth- or fifth-order cycle. In general, the coals pinch out to the west and northwest (landward) (Yurko, 1975). In the Ferron Member of Utah, Ryer (1981) found that coals reached their maximum thickness about 10 km landward of the landward termination of each transgressive shoreline sequence. In the Carboniferous of England, Percival (1986) found that the hydromorphic conditions necessary for accumulation of plant debris, and the leaching of underlying paleosols to form albic horizons, were closely associated with marine transgression. Further, as concluded by McCabe and Shanley (1992) for Upper Cretaceous sequences in the western U.S., because peat accumulation and aggradation can keep up with moderate rates of base level rise, the development of raised mires (represented by coal seams) may actually have helped confine transgressions and stabilize shorelines.

Although the data at hand do not allow the correlation of individual fourth- or fifth-order flooding surfaces with the well-known numbered coal zones #0–12 of the Horseshoe Canyon Formation (see earlier section), several general observations can be offered. The most consistently coaly parts of the Horseshoe Canyon Formation are the lowest units, the Strathmore and Hoodoo tongues, which represent coastal lowlands close to the marine basin and most subject to the influence of marine transgression. Whereas the Strathmore does not outcrop and its seams have never been numbered, certainly the outcrop-numbered zones ("seams") #0–7 all fall within the Hoodoo tongue, especially the upper part of that unit. This also suggests there are numerous fifth-order cycles and accompanying flooding surfaces to be investigated in this part of the section. In contrast, the Midland tongue is less coaly, with coal zones separated by thick barren zones, and may only include numbered coal zones ("seams") #8, 9 and 10. The Midland, with less coal and more dominance of pedogenically altered sediments, is interpreted to represent an upslope fluvial floodplain with less marine influence deposited in a somewhat more arid climate, and consequently fewer marine flooding surfaces. The Tolman tongue, deposited in an upper floodplain setting, is characterized by thorough pedogenic alteration and virtually no coal, suggesting little marine influence or flooding surfaces and the most arid climate, except in association with the DMT and coal zone #10 at the base (and perhaps outside this study area to the east and southeast). The Carbon tongue maximum regressive phase may have developed in a more humid climatic phase (D. Eberth, pers. comm., 2002) allowing development of the thick coal zones ("seams") #11 and 12, and probably associated marine flooding surfaces (outside this study area to the east and southeast).

Paleosols and regional regressions

Coals, and evidence of marine influence, are here considered to be intimately associated with the transgressive pressures that attend the base of each fourth- and fifth-order cycle. Similarly, distinct paleosol horizons, and evidence of subaerial exposure, may be intimately associated with the regressive pressures that form the upper portion of each asymmetrical fourth-and fifth-order cycle. In fact, it might be expected that the most intense development of paleosols would be associated with the most strongly regressive parts of each Horseshoe Canyon nonmarine tongue, and of the formation as a whole. Certainly, the Tolman tongue includes the most and best-developed vertisols and calcisols and the poorest development of gleysols and histosols. In addition, channel lags composed of caliche nodules are common. The top of the Carbon tongue is marked by the striking Whitemud spodosol horizon, which is certainly the best-developed individual paleosol in the succession, and is interpreted as the maximum regression point for the entire third-order Dinosaur Park-Bearpaw-Horseshoe Canyon sequence. It is overlain by the regional sub-Battle subaerial unconformity.

In a geological time frame, paleosols form quite rapidly (hundreds to thousands of years) and therefore can be significant quasi-chronostratigraphic markers for correlation in difficult terrestrial sequences (Kraus, 1999). In many cases calcretes can produce bright seismic reflectors, traceable through continental deposits and can be useful for constructing continental sequence stratigraphic interpretations (Hanneman et al., 1994; Kraus, 1999). This concept may be important to exploration and exploitation efforts for contained resources in the Alberta subsurface. According to Kraus (1999), during periods of transgression, aggradation rates on the floodplain should increase and more weakly developed paleosols will be typical. However, during periods of regression, erosion, incision and lesser aggradation rates will dominate, allowing the accumulation of mature and extensive paleosols. McCarthy and Plint (1998) emphasized the importance of recognizing and correlating paleosols between incised valleys as a method of tracing sequence-bounding paleosols over lateral distances in the complex fluvial system of the Dunvegan Formation in Alberta.

Summary

The regionally extensive marine transgression over the top of the Belly River Group (lower Bearpaw tongue, Cycle A) is interpreted as the result of the first pulse of a phase of renewed thrust loading, rapid subsidence and base level rise in the foreland concentrated in southeastern Alberta. This represents the phase of maximum extent of the Bearpaw sea (Fig. 81a). The subsequent period of tectonic quiescence encouraged regression toward the southeast (Strathmore tongue, Cycle A) as sediment supply overcame accommodation. The motif of progressively less extensive transgression and more extensive regression was repeated upward through late Campanian-Maastrichtian time, allowing overall, but noncontinuous, regression to the east and southeast through the middle Bearpaw tongue-Hoodoo (Cycle B), upper Bearpaw tongue-Midland (Cycle C), Drumheller marine tongue-Tolman (Cycle D) and Carbon (Cycle E) strata (Fig. 81b). In addition, there was an overall climatic trend, from most humid to most arid, from the East Coulee to the Tolman tongues, followed by a return to more humid conditions in the Carbon tongue. The regionally extensive, unique unit at the top of the Carbon (Whitemud sandstone) with evidence of subaerial exposure and intense pedogenesis, is interpreted to represent the maximum regression for the third-order Dinosaur Park-Bearpaw-Horseshoe Canyon sequence, capped by the sub-Battle subaerial unconformity.

The concepts mentioned here, of a) the association of coal with transgression and b) the association of paleosols with regression, could be further investigated and applied in more detailed sequence stratigraphic/resource exploitation studies in the WCSB in future. The systematic tracing of both coal zones and paleosol horizons landward into the nonmarine clastic wedge may prove important in correlating and mapping the fourth-order tongues identified in this study, the fifth-order subunits that comprise the individual reservoirs and aquifers, and in delineating the sequence stratigraphic boundaries present.

SHALLOW GAS POTENTIAL

General

The Horseshoe Canyon Formation contains a small, but potentially important, share of the conventional gas reserves of the post-Colorado strata in a small number of pools in the west-central Alberta Plains (Hamblin and Lee, 1997). These reside primarily in sandstone of the lower, shoreline-related facies of the Strathmore and Hoodoo tongues, and in sandstone channels of the middle-upper, fluvial-related facies of the Midland and Carbon tongues (Appendix III). Known gas pools are conspicuously rare in the oxidized siltstone and paleosols of the Tolman tongue, and may form a partial seal for underlying reservoirs in the study area. Most discovered pools are located to the north and west of the study area, where the strata occur at greater depth. The group is predicted to include a very modest proportion of the total gas resource still to be found in WCSB, distributed through a large number of small, shallow pools (Hamblin and Lee, 1997).

In the recent years, since Hamblin and Lee (1997) published their initial estimates, exploration for shallow gas reservoirs has dramatically increased, with concomitant success in numerous discoveries within Horseshoe Canyon strata. However, this clastic wedge, plus the intertonguing Bearpaw Formation to the south and east, and the correlative St. Mary River Formation to the south, are not as well understood as the underlying Belly River Group, and further study and exploration should elucidate additional possibilities. Also, there is (as yet) undetermined coalbed methane potential in these strata. The following two play descriptions were developed from a synthesis of data (Hamblin and Lee, 1997) before the present stratigraphic subdivision was contemplated. Revision of numerical assessments has not yet been attempted for the current units, but is here recommended, when sufficient public data are available.

Lower Horseshoe Canyon, Shoreline Play Family

This established, mature play includes gas-bearing pools and prospects in nearshore-shoreline sandstone deposits of several of the informal units described in the lower Horseshoe Canyon Formation (Strathmore and Hoodoo tongues), including those related sandy tongues that extend basinward into the marine Bearpaw. This play can be conceptually extended to include shoreline-related sandstone bodies of the Midland and Tolman tongues, where preserved to the south. It includes a large area in west-central and northwestern Alberta (Fig. 82). This play area is defined on the west and southwest by the limit of deformation, and on the east and north by the outcrop belt of the unit. The lower portion (lower Horseshoe Canyon/Blood Reserve formations) includes a series of fourth- and fifth-order sandy tongues that extend basinward into the Bearpaw Formation. These are lower delta plain, estuary, and shoreline complexes related to embayed shorelines, oriented south-southwest–north-northeast, with open sea to the southeast (Gibson, 1977; Rahmani, 1983; this study). As a result of the offlapping arrangement of the successively stacked members identified in this study, each should be considered as a separate play, occupying a different play area and offering a different estimate of hydrocarbon potential. In addition, each fourth-order tongue described in this study also includes stacked fifth-order subunits, each of which comprises mappable shoreline-related reservoir trends. No such analysis has yet been attempted, but obviously the potential for new exploration and exploitation is now greatly expanded.

Lower Horseshoe Canyon shoreline deposits are present in the subsurface from about Twp. 5–55, Rge. 15W4 to the disturbed belt in the west (Fig. 82). Modest gas reserves are contained in a small number of moderate-sized pools. The overlying nonmarine, fine-grained deposits and the thin marine shale tongues identified in this study, which separate the shoreline-related sandstone tongues, are the vertical seals for the pools, and updip to the east or southeast. The pinchout of clean sandstone may also create stratigraphic traps. The source of hydrocarbons may be the underlying Bearpaw Formation marine shale, or the adjacent nonmarine, coal-bearing strata.

The initial discovery well was drilled in Sylvan Lake Field in 1960. Discovered gas pools are concentrated in the Leo, Bashaw, and Pembina fields. As of 1997, the largest discovered pool (Bashaw, Edmonton pool No. 1) had initial in-place volume of 862 x 10^6m^3 (Fig. 83). For this play, the mean pool area is 1146 ha, mean net pay is 3.3 m, mean porosity is 23.8%, and mean pool depth is 446 m. As of 1997, there had been a total of 18 pools discovered in this play and the total discovered in-place volume was 1 237 x 10^6m^3, with a mean in-place pool size of 72 x 10^6m^3.

Estimates of the expected potential for this play (Fig. 83) indicate an in-place volume of 9714 x 10^6m^3 representing approximately 89% of the total play resource, assuming a total population of 580 pools, with an in-place volume for the largest undiscovered pool of 324 x 10^6m^3 (Hamblin and Lee, 1997). The potential gas resources in this play will likely be found in many, modest-sized pools located in west-central Alberta.

Middle–Upper Horseshoe Canyon, Nonmarine Fluvial Play Family

This established, mature play includes gas-bearing pools and prospects in fluvial channel sandstone bodies of the

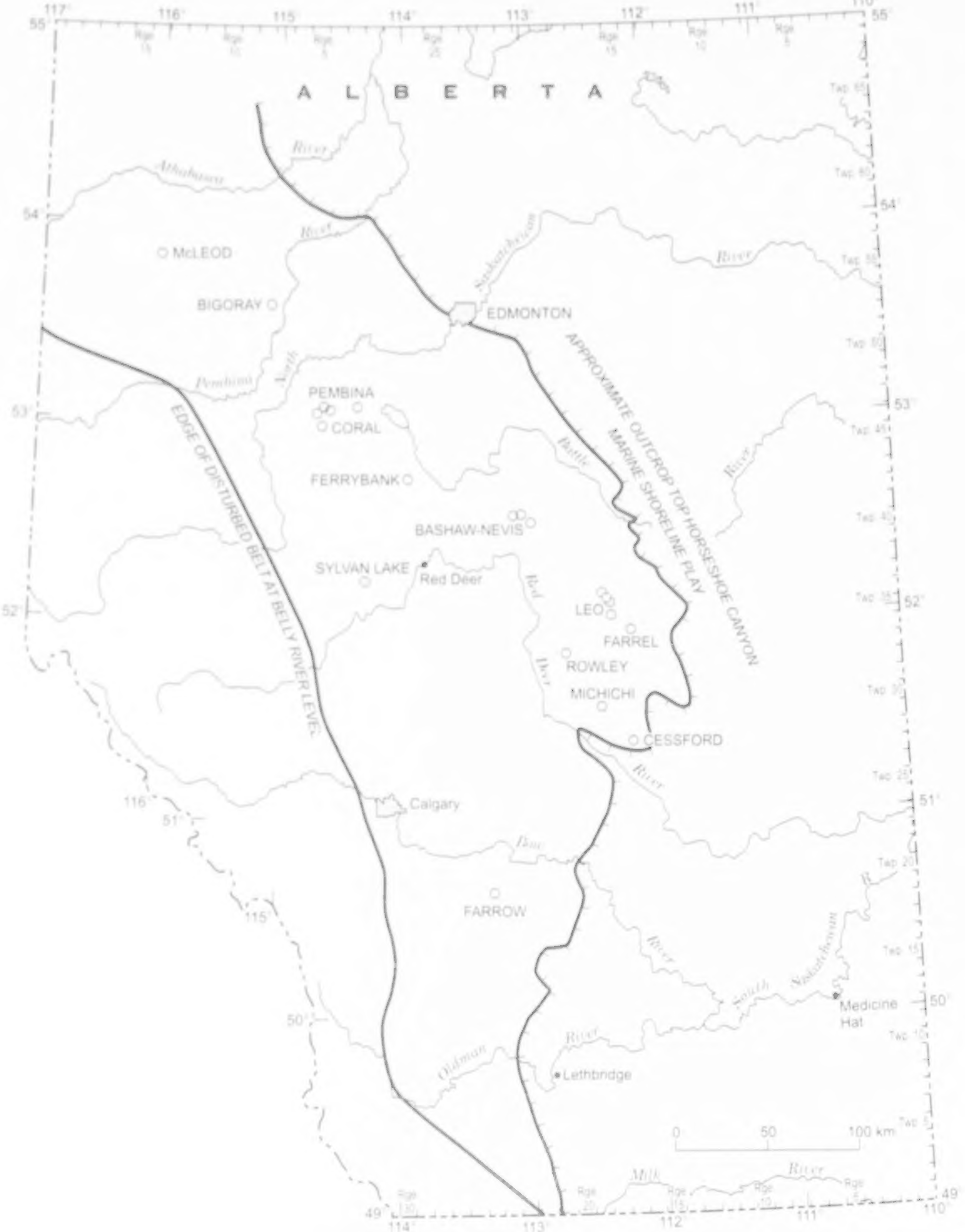
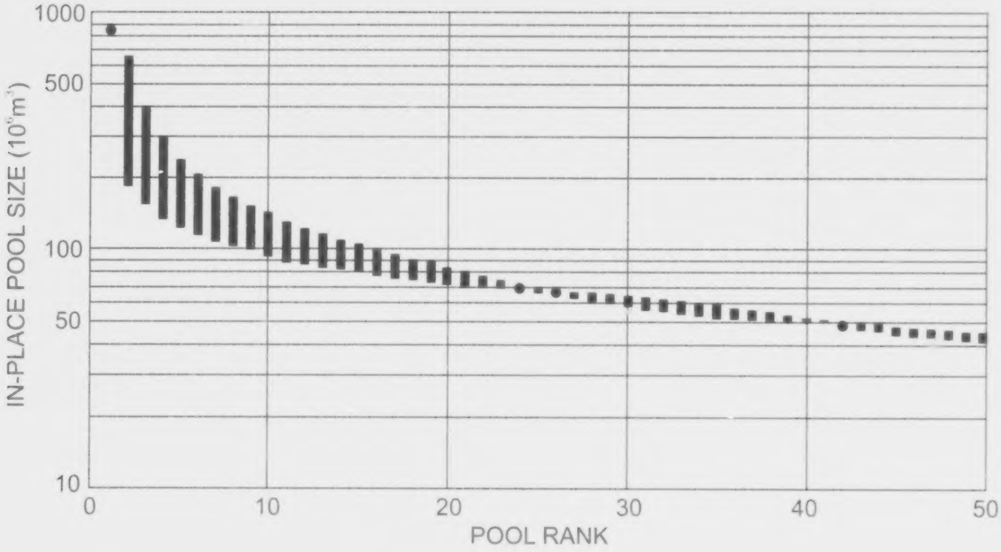


Figure 82. Play area and discovered gas pools, lower Horseshoe Canyon Formation, Marine Shoreline Play Family (primarily Strathmore and Hoodoo tongues) (from Hamblin and Lee, 1997).



Pool rank	Field/pool name	Pool type	Discovered in-place volume (x$10^6 m^3$)	Discovery date
1	Edmonton Pool No. 1	NA	862	79/10/26
24	Sylvan Lake, Edmonton	NA	70	60/12/01
26	Link, Edmonton B	NA	68	85/11/29
42	Pembina, Edmonton	NA	50	77/08/26
109	Pembina, Edmonton	NA	25	79/03/01
114	McLeon, Edmonton	NA	24	79/12/02
185	Michichi, Edmonton	NA	15	89/06/01
186	Pembina, Edmonton	NA	15	82/11/15
210	Fenn West, Edmonton	NA	13	89/10/06
211	Link, Edmonton A	NA	13	85/09/06
241	Michichi, Edmonton	NA	11	77/12/11
242	Michichi, Edmonton	NA	11	89/07/31
259	Farrow, Edmonton	NA	10	74/08/05
260	Leo, Edmonton	NA	10	79/12/07
280	Cessford, Edmonton A	NA	9	81/01/02
327	Coral, Paskapoo	NA	7	78/03/05
426	Farrell, Edmonton	NA	4	84/08/25
Initial in-place volume (discovered) ($10^6 m^3$)			1 237	
Initial in-place volume (potential) ($10^6 m^3$)			9 714	
Per cent play resources undiscovered			89	
Total pools discovered			18	
Total pool population			580	

NA, nonassociated gas

Figure 83. *Pool-size-by-rank plot, showing the top 50 pools (discovered and undiscovered), and a summary of the largest pools discovered, lower Horseshoe Canyon Formation, Marine Shoreline Play Family (primarily Strathmore and Hoodoo tongues) (from Hamblin and Lee, 1997).*

lower, middle and upper Horseshoe Canyon Formation (primarily, the Hoodoo, Midland, Tolman, and Carbon tongues). This play type can be conceptually extended to include channel sandstone bodies of the Strathmore and Hoodoo tongues to the north and west. It includes a large area in west-central Alberta (Fig. 84). This play area is defined on the west and southwest by the limit of deformation, and on the east and north by the outcrop belt of the unit. Most of the Horseshoe Canyon Formation of central Alberta, and the St. Mary River Formation in

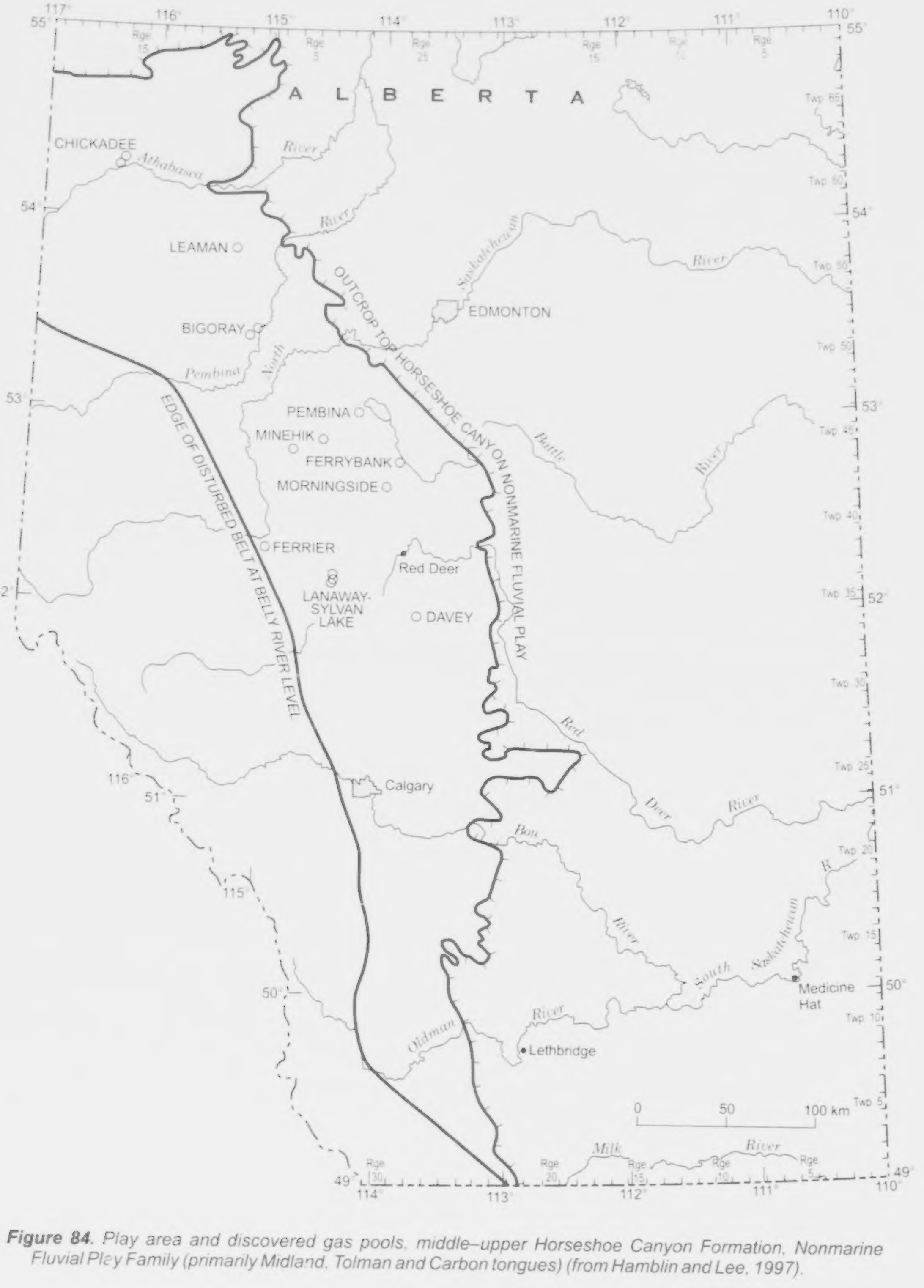


Figure 84. *Play area and discovered gas pools, middle–upper Horseshoe Canyon Formation, Nonmarine Fluvial Play Family (primarily Midland, Tolman and Carbon tongues) (from Hamblin and Lee, 1997).*

southwestern Alberta, include upper delta plain, interbedded, thick, fluvial channel sandstone and overbank mudstone with thick coal deposited behind the shoreline complexes of the Horseshoe Canyon clastic wedge (Gibson, 1977; this study). Throughout much of southern Alberta these deposits are blanketed by the bentonitic mudstone of the Battle Formation (Irish, 1970; this study).

Middle and Upper Horseshoe Canyon fluvial deposits are present in the subsurface beneath all of western Alberta, from about Twp. 5–60, Rge. 23W4 to the disturbed belt in the west (Fig. 84). Minor gas reserves are contained within a few small pools. The overlying and interbedded nonmarine, fine-grained deposits within the Horseshoe Canyon and Battle formations, and the interbedded thin marine tongues that separate the sandy formations of the Horseshoe Canyon Formation, are the vertical seals for the pools in fluvial channels that create stratigraphic traps. The source of hydrocarbons may be the underlying Bearpaw Formation marine shale, or the interbedded nonmarine, coal-bearing strata.

The initial discovery well was drilled in the Bigoray Field in 1958. Discovered gas pools are scattered through central Alberta. As of 1997, the largest discovered pool (Pembina, Edm) had an initial in-place volume of 128 x 10^6m^3 (Fig. 85). For this play, the mean pool area is 203 ha, mean net pay is 5.5 m, mean porosity is 24.8%, and mean pool depth is 525 m. As of 1997, there had been a total of 17 pools discovered in this play and the total discovered in-place volume was 532 x 10^6m^3, with a mean in-place pool size of 31 x 10^6m^3.

Estimates of the expected potential for this play (Fig. 85) indicate an in-place volume of 5834 x 10^6m^3, representing approximately 92% of the total play resource, assuming a total population of 600 pools, with an in-place volume for the largest undiscovered pool of 335 x 10^6m^3 (Hamblin and Lee, 1997). The potential gas resources in this play will likely be found in many, rather small pools situated in the Plains of west-central Alberta.

COALBED METHANE POTENTIAL

General

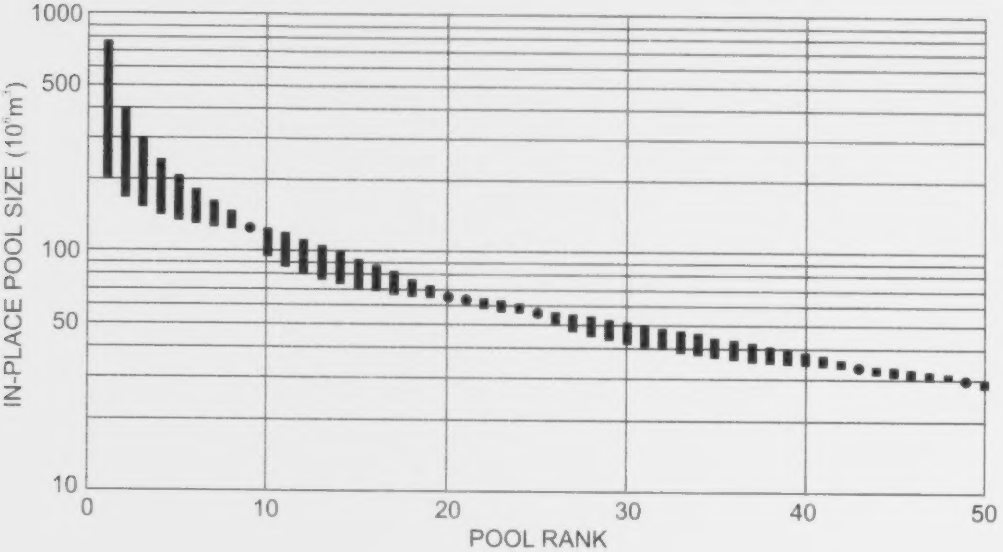
Coalbed methane production has become an important energy resource in the U.S., and interest in Canada is increasing rapidly. Methane is generated during the coalification process as a function of the temperature to which the coal is heated during burial (CGPC, 2001). The gas content increases with maturity and peaks in coals of high-volatile bituminous rank (CGPC, 2001). The successful generation, storage and producibility of coal gas from coal seams is dependant on 1) the rank, composition, ash content and thickness of the coal seams; 2) the depth and thermal history; and, especially 3) the micro-and macro-permeability within the seams, primarily a function of fracture (cleat) systems (Dawson et al., 2000; CGPC, 2001). The volumes and nature of produced waters is also clearly of great environmental importance.

Over the last 120 years, more than 1200 mines (mostly strip operations) producing lignitic to high-volatile bituminous coal (mostly subbituminous), were registered in the Plains region of Alberta alone (Smith, 1989). There has been little deformation of these coals, although they have been affected by differential compaction, and rank generally increases to the west with increasing depth (Smith, 1989). Although the volume of gas in place is likely to be large and widely dispersed, well productivity tends to be low, production costs are high and pre-production extensive pilot projects are required to assess feasibility (CGPC, 2001).

Coals of the Upper Cretaceous of the Interior Plains formed primarily in deltaic and alluvial environments near, and landward of, marine shorelines (Smith, 1989; this study). Peat accumulation was most prominent in marsh areas remote from clastic input from fluvial channels and in backshore depressions. Hamblin (1997b) interpreted the aggradation of the Lethbridge Coal Zone at the top of the Belly River Group as related to the extensive, rapid base level rise and transgression of the basal Bearpaw marine shale. Likewise, many of the thickest, best-developed coal seams in the Horseshoe Canyon Formation are present immediately beneath the flooding surfaces marking the incursions of Bearpaw marine tongues that separate the enclosed cycles and nonmarine tongues identified in this study. The concept of thick seams being closely associated with stable aggrading or transgressive shorelines was first elucidated by Sears et al. (1941) and Fassett and Hinds (1971). The Horseshoe Canyon coals are also here interpreted to be related to periodic, repeated, rapid base level rise and marine transgression linked to regional control of subsidence.

Horseshoe Canyon Formation

Although the Horseshoe Canyon Formation of the Alberta Plains is not considered a prime candidate for large coalbed methane resources, there are factors that suggest the potential is worth appraisal. Dawson et al. (2000) noted that seam thickness and lateral continuity, coal rank and vitrinite content, and gas content could be similar to the seams of the Scollard Formation, which are the target for several intensive coalbed methane pilot projects in southern Alberta. In addition, other favourable factors for the Horseshoe Canyon Formation include the shallow depth to intersection, gentle structural folding, generally fresh water content, and location in the Plains where a large land



Pool rank	Field/pool name	Pool type	Discovered in-place volume ($x10^6 m^3$)	Discovery date
9	Pembina, Edmonton	NA	128	78/11/08
20	Bigoray, Paskapoo	NA	66	58/11/13
21	Ferrier, Edmonton	NA	65	85/10/13
25	Minnehik-Buck Lake, Edmonton	NA	57	78/01/22
43	Davey, Edmonton	NA	34	77/08/03
49	Pembina, Edmonton	NA	30	88/02/20
60	Ferrybank, Edmonton	NA	24	79/11/01
65	Chickadee, Edmonton	NA	22	80/04/23
71	Leaman, Edmonton	NA	20	77/08/27
73	Minnehik-Buck Lake, Edmonton	NA	19	79/12/28
74	Morkill, Edmonton	NA	19	77/01/01
86	Bigoray, Edmonton	NA	16	78/03/02
96	Ferrybank, Edmonton	NA	14	77/07/03
146	Pembina, Edmonton	NA	8	80/10/02
197	Morningside, Edmonton	NA	5	80/08/13
224	Bigoray, Paskapoo A	NA	4	71/05/28
397	Chickadee, Edmonton A	NA	1	80/10/02
Initial in-place volume (discovered) ($10^6 m^3$)			532	
Initial in-place volume (potential) ($10^6 m^3$)			5 834	
Per cent play resources undiscovered			92	
Total pools discovered			17	
Total pool population			600	

NA, nonassociated gas

Figure 85. *Pool-size-by-rank plot, showing the top 50 pools (discovered and undiscovered), and a summary of the largest pools discovered, middle–upper Horseshoe Canyon Formation, Nonmarine Fluvial Play Family (primarily Midland, Tolman and Carbon tongues) (from Hamblin and Lee, 1997).*

position can be assembled to develop a multi-well program (Dawson et al., 2000). As reviewed below, these coals are known to produce significant volumes of fresh water, confirming the presence of permeability and fractures.

There has been a long-term economic interest in the coals of the Horseshoe Canyon Formation, which account for most of the accessible reserves on the Plains and are currently used for electrical generation (Yurko, 1975;

McCabe et al., 1989). More recently, interest has focussed on the coalbed methane potential. In the valley of the North Saskatchewan River near Edmonton, the coal seams were first described by Tyrrell (1887), and studied in detail by Dowling (1910), Beach (1934) and Pearson (1961). Here are up to ten poorly exposed seams generally less than 2 m thick, of which four were mined extensively in the first half of the 20th century (Pearson, 1961). All coals are of subbituminous B/C grade. The Clover Bar Coal Zone (or #4 seam) was the most intensively studied, and actually comprises several less continuous seams 1 to 2 m thick, separated by thin shale beds (Pearson, 1961).

In the Red Deer River Valley, coal seams were first described by Tyrrell (1887), and first studied in detail by Allan (1921) and Allan and Sanderson (1945). The coals exposed at surface are concentrated into ten commercial "zones" between the base of the Horseshoe Canyon Formation and the Drumheller marine tongue (many coals in the Hoodoo tongue, few in the Midland and Tolman tongues), and two persistent horizons above the Drumheller marine tongue (within the Carbon tongue). The Horseshoe Canyon Formation has about 19 500 megatonnes of defined resource in 13 coalfields along the outcrop and subcrop belt (Dawson et al., 2000). The seams are thickest near the outcrop belt and thin rapidly to zero as the rank increases to the west (Yurko, 1975). There is rapid thinning and thickening of individual seams over short distances, making seam correlation difficult, although the "coal zones" tend to be somewhat more extensive and continuous (Allan and Sanderson, 1945; Yurko, 1975; McCabe et al., 1989). Areas of thicker coal accumulation also generally have thicker seams (McCabe et al., 1989).

The lower Horseshoe Canyon Formation is most important for coal, with continuous seams with thin clastic partings ("Drumheller Coal Zone" of McCabe et al., 1989), which represent widespread shore-parallel peat mires that accumulated during times of low sediment input (Allan and Sanderson, 1945; McCabe et al., 1989). The best coals are associated with the many tongues of marine influence that characterize the lower transitional 50 m of the formation, hence the extent of marine strata of the Bearpaw and Drumheller marine tongue are conceptually important (McCabe et al., 1989; Dawson et al., 2000). This study also illustrates transgressive marine tongues of greater regional extent and their relation to coal concentration. These coals were deposited in shoreline-parallel peat swamps 30–50 km back of the actual shoreline (McCabe et al., 1989). Repeated transgressive-regressive phases resulted in extensive stacked coal seams with thicknesses over 2 m (McCabe et al., 1989). These are organized into north-south trends, especially well-developed west of the outcrop belt (McCabe et al., 1989). According to Gibson (1977), the coals are associated with three types of sandstone deposits: 1) coarsening-upward bayfills, 2) thick northeast-trending channels, 3) thin fining-upward crevasse splays.

Coals in the upper Horseshoe Canyon Formation are encased in predominantly sandy fluvial sediments, are less continuous, and follow different trends (McCabe et al., 1989). Nurkowski (1980) and Nurkowski and Rahmani (1984) studied the coal-bearing unit 60 to 80 m thick at the top of the Horseshoe Canyon Formation in central Alberta and described a general coarsening-upward, more fluvial-upward, succession deposited on a broad, low-lying coastal plain west and north of the retreating Bearpaw sea. This unit is under- and overlain by bentonitic markers interpreted to be synchronous time lines. The Carbon Coal Zone has thick channel sandstone deposits, overbank laminated mudstone, and coal seams up to 4 m thick, distributed in northwest-southeast trends beside and parallel to channel trends, and only correlatable along these trends. The overlying Thompson Coal Zone has coarser sandstone channel deposits, mudstone and seams that, likewise, parallel the northwest-southeast channels in sinuous bands.

In this report it is suggested that an intimate genetic relationship exists between coal zones and marine transgression (on both regional fourth-order, and local fifth-order scales). Utilizing this concept may lend much more predictability to the exploration of seams in this formation. Trends of coal thickness in the lower Horseshoe Canyon Formation generally follow northeast-southwest directions (McCabe et al., 1989), approximately parallel to interpreted shoreline trends. Coals of the Strathmore tongue, present only in the subsurface, have never been part of the numbered system of seams established in outcrop, and therefore may represent a new exploration target. Conversely, in the upper Horseshoe Canyon, trends of coal thickness apparently parallel channel trends, approximately northwest-southeast (Nurkowski, 1980; Nurkowski and Rahmani, 1984). These concepts may provide new approaches and predictability for further exploration and exploitation of the coalbed methane potential of these strata.

In addition, conventional gas pools known from the Horseshoe Canyon Formation sandstone may, in fact, tap into gas reserves present in associated coal seams. Certainly, gas is produced from many sandstone bodies that are stratigraphically adjacent to coal seams, particularly in the Strathmore and Hoodoo tongue of the lower Horseshoe Canyon Formation. This concept of exploiting a high-quality conventional sandstone reservoir sourced directly from an adjacent gas-rich coal seam may provide the necessary stimulus to economically produce coalbed methane in the Plains.

Coal rank is generally low in these rocks (coals of the Horseshoe Canyon Formation are generally subbituminous

C in rank: Smith, 1989) and consequently they have low gas contents, but economic volumes could be obtained by a large array of wells. This strategy is currently being employed for other stratigraphic units in a large pilot project by an industry consortia in southeastern Alberta, with anticipated positive results (Dawson et al., 2000). Macleod et al. (2000) provided a preliminary assessment of coalbed methane resource potential in the Plains of Alberta and suggested about 16 Tcf of gas in situ in the Horseshoe Canyon Formation. This conclusion was recently confirmed by Alberta Energy and Utilities Board (Beaton et al., 2002). Langenberg and Pana (2002) studied the "Drumheller coal zone" (i.e., Hoodoo tongue of this report) in the Alix area and suggested that estimated gas contents of up to 100 million cubic metres of methane per square kilometre could exist in a north-south-trending belt through Twp. 39–40, Rge. 23W4. This might present a possible location for testing the coalbed methane potential of the Horseshoe Canyon Formation (Langenberg and Pana, 2002). Most recently, commercial production of gas from Horseshoe Canyon seams has now become a reality (Wirth and Hysert, 2003).

Further detailed mapping of coal seam and zone distribution in the near-surface setting, stratigraphy and sedimentology of the enclosing sediments, desorption testing of these coals and study of subtle structural drape and fracturing should make clearer the potential for coalbed methane resources in the strata of the Horseshoe Canyon Formation. However, important environmental questions associated with the production of this gas must also be addressed.

WATER RESOURCE POTENTIAL

General

In the Alberta Plains, groundwater has been traditionally used for agricultural purposes. On farms the water is used in small-scale domestic and stock-watering operations, and a few small villages have always used underground supplies (Stein, 1982). However, through time, the amount of groundwater tapped for municipal and industrial use has increased dramatically, as rural Alberta has become more urbanized and industrialized. This trend will likely continue and both the need for, and the environmental pressure on, groundwater aquifers will increase. Surficial (Quaternary) deposits have always provided significant resources, but bedrock aquifers within 300 m of surface are the main source in some areas and generally provide much softer water (Kunkle, 1962). In general bedrock aquifers yield modest flows of water with modest chemical quality (Kunkle, 1962; Borneuf, 1979).

Bearpaw Formation

The Bearpaw marine shale contains little fresh water in most areas because of general low permeability and the lack of obvious aquifer facies. In fact, the Bearpaw underlies much of the southern Prairies of Alberta and provides a regional seal to downward movement of water (VandenBerg and Lennox, 1969). However, in the Castor, Coronation, and Oyen areas of east-central Alberta, porous and permeable sandstone members are present in the upper portion of the formation (Foster and Farvolden, 1958; Kunkle, 1962; LeBreton, 1963; Borneuf, 1979) which have supplied strong, but limited, flows.

These sandstone units, referred to as the Bulwark Member, represent tongues of the Horseshoe Canyon continental wedge that extend southeastward into the Bearpaw marine shale (likely correlative to the Strathmore, Hoodoo or Midland tongues of this study). As already described in this report, these fourth- and fifth-order tongues are a normal manifestation of the Bearpaw-Horseshoe Canyon transition, and should be common throughout southern Alberta. The friable, very fine- to medium-grained sandstone occurs in several distinct overlapping bodies up to 5 m thick that likely extend over lateral distances of 2–20 km (Borneuf, 1979). They generally yield up to 2 L/s flows from aquifers of limited extent and relatively short lifespans (Kunkle, 1962), although Borneuf (1979) reported that pumptesting can yield up to 40 L/s in small areas. The waters have significant dissolved solids (less than 1000 mg/L), are rich in Na-bicarbonate and relatively low in sulphate (Kunkle, 1962; Borneuf, 1979).

More detailed mapping of near-surface sandstone tongues within the Bearpaw Formation is possible in many areas and therefore potential for additional limited water resources from the Bearpaw is high. For example, this study has identified the previously undocumented Strathmore tongue, a completely subsurface tongue of the Horseshoe Canyon Formation, for the first time, and other units delineated in this report could be mapped beyond the confines of the study area.

Horseshoe Canyon Formation

The Horseshoe Canyon Formation includes thinly interbedded sandstone, shale, and coal and provides major groundwater aquifers in several areas of the Alberta Plains. The most important hydrological features of the formation are the same characteristics Irish (1970) noted of the strata: great variety of lithologies, predominance of discontinuous or lens-shaped stratal bodies, abundant bentonite and other clays, and the numerous coal seams arranged into distinct stratigraphic zones (Foster and Farvolden, 1958; Stein, 1982). In addition, the interdigitation of shaly marine aquitard tongues and the basinward offlap and pinchout of sandy, nonmarine aquifer tongues, as illustrated in this report, are important factors for scoping studies. Both the fourth-order tongues described and mapped in this report for the first time, and the nested fifth-order subunits have important potential for groundwater resources. It is anticipated that shoreline-related sandstone bodies will trend generally northeast-southwest, and channelized fluvial and estuarine sandstone bodies will trend generally northwest-southeast. Although the deposits generally have very low permeability and transmissivity, there are some sandstone lenses that are good aquifers (Bibby, 1974), producing unassisted yields of 1 L/s and pumped flows of up to 5 L/s of Na-bicarbonate water, from sandstone bodies greater than 3 m thick (Kunkle, 1962; VandenBerg and Lennox, 1969). In these deposits, yields are quite variable (Foster and Farvolden, 1958). These porous and permeable sandstone lenses represent channel deposits within the muddy coastal plain deposits that make up the bulk of the Horseshoe Canyon Formation.

However, VandenBerg and Lennox (1969) noted that in many areas, the primary flow component in the Horseshoe Canyon is vertical (across the bedding), suggesting the importance of fracturing. Borneuf (1972) found that fractured sandstone in the Drumheller area yielded substantial flows of up to 15 L/s of Na-bicarbonate-rich waters (with significant sulphate content in some locations), whereas LeBreton (1963) noted excellent flows of up to 35 L/s in the Red Deer area. Clearly, the interpreted fracturing is sufficient to overcome the natural impermeabiliity of the thinly interbedded bentonite- and montmorillonite-rich sediments (Foster and Farvolden, 1958).

Most studies in the Edmonton area have found that the best aquifers are fractured coal seams, particularly in the lower 150 m of the Horseshoe Canyon Formation (Foster and Farvolden, 1958; Bibby, 1974; Stein, 1976, 1982). Fracturing, and the subsequent creation of permeability, may be due to glacial overriding, gentle structural drape over underlying Paleozoic reefs or thick channel sandstone bodies, and postglacial anticline formation and brecciation after overburden erosion (Stein, 1976, 1982; Parks and Tóth, 1995; Dawson et al., 2000). Fracturing extends many tens of metres into the subsurface, although it does decrease with depth (Stein, 1976, 1982). Parks and Tóth (1995) found evidence that the Horseshoe Canyon deposits possess rock-mechanical properties favourable to elastic rebound behaviour after erosional overburden removal. Good flows are obtained from individual coal seams 1–5 m thick, which commonly occur as multiple, splitting and coalescing components of a more areally extensive coal zone. Near Edmonton, the Clover Bar Coal Zone yields 8–150 L/s of Na-bicarbonate-rich water, with 1000–1500 mg/L dissolved solids, from fractured coal seams (Stein, 1976, 1982). The fact that large volumes of water are produced certainly indicates permeability in the coals and may also indicate significant potential for coalbed methane resources (Dawson et al., 2000).

Further detailed mapping of sandstone channel and shoreline aquifers within each of the identifiable fourth- and fifth-order cycles, as described in this report, identification of subtle structural drape and fracturing, and study of coal seam and zone distribution in the near-surface setting should elucidate greater potential for groundwater resources in the very variable deposits of the Horseshoe Canyon Formation.

CONCLUSIONS

1. Both surface outcrop lithologies and subsurface gamma ray-porosity log signatures of sandstone-dominated upper Campanian–Maastrichtian strata are sufficiently distinctive to be used for recognition, correlation, mapping, and subdivision of important, regionally extensive internal units, which include shallow-gas reservoirs, gas-rich coal seams, and groundwater aquifers in the study area in south-central Alberta.

2. The upper Campanian–Maastrichtian Horseshoe Canyon Formation represents the regressive portion of the third-order Dinosaur Park-Bearpaw-Horseshoe Canyon Sequence, primarily of tectonic origin, within the Western Interior Foreland Basin, which spread southeastward into the Bearpaw sea. In south-central Alberta it can be subdivided into five, previously unrecognized lithostratigraphic tongues that form the nonmarine portions of asymmetrical regressive fourth-order cycles. To the southeast, these are separated by thin, previously unrecognized tongues of marine, mudstone-dominated strata of the partly coeval Bearpaw Formation.

3. The "base" of the Horseshoe Canyon Formation is not a single stratigraphic contact, but is highly diachronous and represented by multiple Horseshoe Canyon-Bearpaw transitions in different areas, as a result of the lateral and vertical stacking of regressive fourth-order cycles.

4. The Drumheller marine tongue, previously treated as a unique marine incursion within the Horseshoe Canyon, is actually one of at least four, regionally extensive, marine tongues, the identification of which are key to delineating the internal organization and understanding of this clastic wedge.

5. The Strathmore tongue (new informal unit) comprises thinly interbedded fine-grained sandstone, siltstone, carbonaceous mudstone, and coal, deposited in paralic settings. It is present only in the subsurface of the study area, passing southeastward into Bearpaw marine shale before rising to outcrop. It is underlain by the Belly River Group or the lower Bearpaw tongue, and is overlain by the Hoodoo tongue or the middle Bearpaw tongue.

6. The Hoodoo tongue (new informal unit) comprises interbedded, thick, channelized fine-grained sandstone, siltstone, and abundant thick coals, deposited in paralic and estuarine settings. It is present in the study area in the subsurface and outcrops in the Red Deer River valley southeast of Drumheller. It is underlain by the Strathmore tongue or the middle Bearpaw tongue, and is overlain by the Midland tongue or the upper Bearpaw tongue.

7. The Midland tongue (new informal unit) comprises thinly interbedded, channelized, fine-grained sandstone, siltstone, and coal, deposited in meandering fluvial and coastal floodplain overbank settings. It is present in the study area in the subsurface and outcrops in the valleys of the Red Deer River, Rosebud River, and Kneehills Creek. It is underlain by the Hoodoo tongue or the upper Bearpaw tongue, and is overlain by the Tolman Member or the Drumheller marine tongue.

8. The Tolman tongue (some similarities to the Tolman member of Srivastava, 1968) comprises greenish pedogenic siltstone and thin, fine-grained sandstone with virtually no coal, deposited in a floodplain overbank setting. It is present in the study area in the subsurface and outcrops in the valleys of the Red Deer River, Rosebud River, and Kneehills Creek. It is underlain by the Midland tongue or the Drumheller marine tongue, and is overlain by the Carbon tongue.

9. The Carbon tongue (new informal unit) comprises thickly interbedded, channelized, fine-grained sandstone, siltstone, and thick coals, with the distinctive Whitemud sandstone at the top. These strata were deposited in channel and overbank environments of a fluvial floodplain setting. It is present in the study area in the subsurface and outcrops in the valleys of the Red Deer River, Rosebud River, and Kneehills Creek. It is underlain by the Tolman tongue, and is unconformably overlain by the Battle Formation.

10. Poorly to moderately developed paleosols of various types, previously not emphasized, figure prominently in several units of the Horseshoe Canyon Formation, and include 1) vertisols and gleysols (in Hoodoo, Midland, and Tolman tongues) manifest as greenish grey, massive, blocky siltstone with peds; 2) calcisols (in Hoodoo, Midland, and Tolman tongues) manifest as distinct horizons of rusty sideritic nodules and concretions; 3) spodosols (especially the prominent albic Whitemud sandstone of the Carbon tongue) manifest as white leached quartz- and kaolinite-rich sandstone beneath organic-rich beds; and 4) histosols (in Strathmore, Hoodoo, and Midland tongues) manifest as lignitic to vitreous coal seams with roots. All paleosol types are typical of low-slope, poorly drained floodplain settings and suggest fairly rapid basin subsidence and sediment supply. The leached Whitemud sandstone marks the unconformable top of the third-order upper Campanian–Maastrichtian sequence.

11. The abundant vertisols imply a generally humid climatic regime, but with a distinct drying season. However, from the Strathmore tongue upward to the Tolman tongue, the number, thickness, and quality of coal seams decreases as the number, thickness and maturity of the paleosols increases. This suggests an overall drying paleoclimatic trend, followed by a return to more humid conditions during deposition of the Carbon tongue.

12. New paleocurrent data and map distribution data from this study extend and complement previous interpretations of Horseshoe Canyon sediment dispersal. A total of 436 direct and 133 indirect paleoflow indicators, from 39 outcrops, indicates sediment dispersal to the east-southeast toward the Bearpaw marine basin, with shorelines oriented approximately north-northeast–south-southwest.

13. Paleocurrent data from each of the four informal tongues that outcrop show similar trends, but also indicate a minor shift in sediment dispersal from southeastward paleoflow to eastward paleoflow near the top of the Horseshoe Canyon Formation. Continuing this trend, the overlying Scollard Formation deposits record northeastward paleoflow.

14. The importance of relatively rapid basin subsidence is indicated by the prominence of 1) regional vertical aggradation of successive units dominating over lateral offlap; 2) abundant thick coal seams in numerous more laterally continuous coal zones; and 3) abundant stacked paleosols of varieties typical of low-slope, poorly drained settings.

15. The bulk of the Horseshoe Canyon Formation represents an extended third-order period of base level rise during which a long-term trend of sediment supply dominating over basin subsidence and accommodation space allowed noncontinuous southeastward

progradation of these cycles over hundreds of kilometres during a 6 to 7 Ma interval. Maximum progradation was achieved at the top of the Carbon tongue, marked by the distinctive spodosol horizon of the Whitemud sandstone and the regional sub-Battle subaerial unconformity.

16. The five newly identified tongues represent components of five (offlapping and vertically aggrading) regionally correlatable, asymmetrical fourth-order transgressive-regressive cycles. These include lower, thin marine tongues, and upper, primarily regressive, sandy-coaly, nonmarine wedges. In general, each succeeding marine tongue, originating in the southeast, extended less distance to the northwest, and each succeeding nonmarine sandy tongue extended farther to the southeast in an overall regressive pattern as the Bearpaw sea was gradually overcome by the clastic sediment supply from the northwest. Each fourth-order cycle spans about 1 to 2 Ma.

17. In addition, nested within each fourth-order cycle are several smaller-scale correlatable genetic subunits (asymmetrical fifth-order cycles) which may equate to individual reservoir and aquifer trends. The well-known portion of the lower Horseshoe Canyon Formation studied by previous authors at Willow Creek (here included in the Hoodoo tongue), is one of these fifth-order cycles. Sandstone facies tracts include both coarsening-upward (progradational shoreface) successions and fining-upward, channelized (regressive fluvial and/or transgressive estuarine) successions.

18. There may be an intimate association of best coal seam development with phases of marine transgression, and of best vertisol, calcisol, and spodosol development with phases of nonmarine regression. This concept may have further application in more detailed delineation and mapping of individual reservoir and aquifer bodies within fifth-order cycles, which have potential for coalbed methane, hydrocarbon, and groundwater resources.

19. A significant number of gas pools (most resulting from serendipitous discoveries until 1997, but more recently through concerted exploration programs) are known from the Horseshoe Canyon Formation of south-central Alberta, distributed through all five new tongues. Utilizing the regional framework of fourth-order, and nested fifth-order, cycles presented in this study to direct exploration efforts (and "bypassed pay" assessment) in this previously ignored target zone has potential for many additional shallow gas pool discoveries of small to moderate size. These may occur primarily in northwest-southeast-trending channel and estuarine bodies and in northeast-southwest-trending shoreface-related sandstone reservoirs within each cycle.

20. The abundant thick coal seams that characterize the lower Horseshoe Canyon Formation in the study area are especially well-developed in trends parallelling northeast-southwest shorelines and in association with the flooding surfaces of transgressive Bearpaw marine tongues. They present significant, but as yet unassessed, coalbed methane potential where these strata reside at relatively shallow depths. Coals in the upper Horseshoe Canyon parallel the northwest-southeast channel trends. Application of the regional framework derived in this study may improve the delineation of stratigraphic intervals and geographic trends with coalbed methane potential. Exploration strategies involving identifying combinations of porous and permeable sandstone bodies with adjacent coals, and large arrays of production wells, may improve the economic potential of Horseshoe Canyon coalbed methane targets.

21. Shoreline and channel sandstone units within the Bearpaw-Horseshoe Canyon regressive complex have yielded strong flows of groundwater rich in Na-bicarbonate and with low sulfur content, possibly associated with near-surface fracturing and coal seams. Conceptual extension and application of the principles of the regional framework derived from this study should considerably assist efforts to understand the potential for shallow, bedrock-hosted groundwater resources. Northwest-southeast-trending channelized, and northeast-southwest-trending shoreface sandstone bodies may provide significant aquifers. Further detailed study and mapping is necessary to evaluate this important potential resource.

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Appendix A
Measured sections, locations, and raw paleocurrent data

Southeast-northwest Red Deer River Transect. Approximately 100 km. along depositional dip and across structural strike. See Figure 2a for composite map showing locations of all sections.

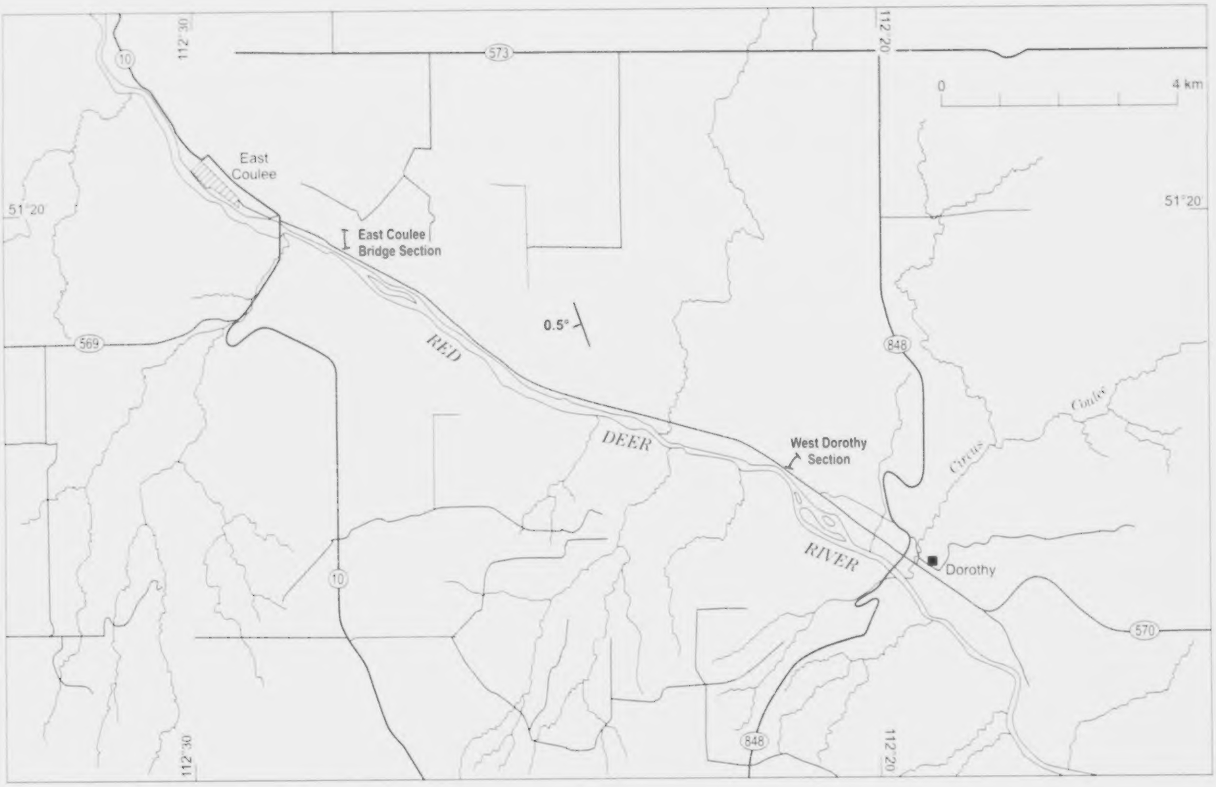
Outcrop Core	Latitude; Longitude	Section Township Range	1:50 000 NTS Sheet	NTS Grid Location	Stratigraphic Interval
West Dorothy	51°18'N; 112°21'W	8-27-17 W4	Dorothy	056835	upper Bearpaw
East Coulee Bridge	51°20'N; 112°28'W	28-27-18 W4	Dorothy	981873	upper Bearpaw-Hoodoo
Hoodoos	51°23'N; 112°32'W	7-28-18/19W4	Drumheller	931932	upper Bearpaw-Hoodoo
Aerial Suspension Bridge	51°25'N; 112°36'W	27-28-19 W4	Drumheller	882973	Hoodoo-Midland
Drumheller East	51°27'N; 112°41'W	1-29-20 W4	Drumheller	832019	Hoodoo-Midland
Highway #9, Drumheller	51°29'N; 112°43'W	14-29-20 W4	Drumheller	808049	Hoodoo-Midland
Drumheller South	51°27'N; 112°43'W	2-29-20 W4	Drumheller	804008	Hoodoo
Highway 575 Roadcut	51°29'N; 112°49'W	18-29-20 W4	Drumheller	742044	Midland
Orkney Hill	51°32'N; 112°53'W	4-30-21 W4	Munson	689107	Midland-Tolman
Bleriot Ferry	51°34'N; 112°54'W	16-30-21 W4	Munson	685145	Midland-Tolman
Morrin Bridge	51°38'N; 112°54'W	10-31-21 W4	Munson	681227	Midland-Tolman
Power Line/Twp. Rd 32-2	51°44'N; 112°57'W	17-32-21 W4	Munson	658336	Tolman-Carbon-Battle
Tolman Bridge	51°51'N; 113°02'W	22-33-22 W4	Trochu	595463	Tolman-Carbon-Battle-Scollard
Dry Island Provincial Park	51°56'N; 112°58'W	30-34-21 W4	Rumsey	650560	Tolman-Carbon-Battle-Scollard

Northeast-southwest Rosebud River Transect. Approximately 30 km. down structural dip and across depositional strike.

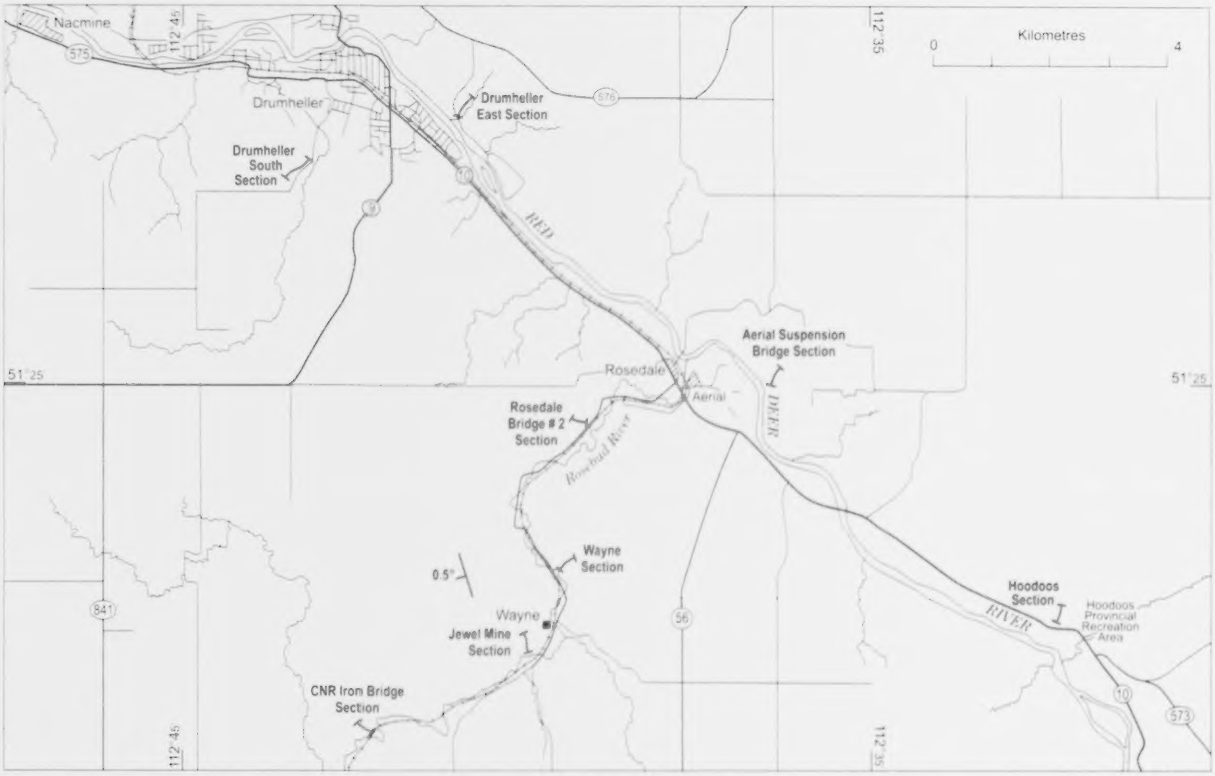
Outcrop Core	Latitude; Longitude	Section Township Range	1:50 000 NTS Sheet	NTS Grid Location	Stratigraphic Interval
Rosedale Bridge #2	51°25'N; 112°39'W	19-28-19 W4	Drumheller	850966	Hoodoo-Midland
Wayne	51°23'N; 112°39'W	18-28-19 W4	Drumheller	847943	Hoodoo-Midland
Jewel Mine	51°23'N; 112°40'W	7-28-19 W4	Drumheller	840930	Hoodoo-Midland
CNR Iron Bridge	51°22'N; 112°42'W	2-28-20 W4	Drumheller	813916	Midland-Tolman
Mile 64.5	51°22'N; 112°43'W	34-27-20 W4	Drumheller	798904	Midland-Tolman
Taylor Siding	51°21'N; 112°45'W	33-27-20 W4	Drumheller	776895	Midland
Beynon Ecological Preserve	51°20'N; 112°47'W	29-27-20 W4	Drumheller	754882	Midland-Tolman
Mile 70.5	51°20'N; 112°49'W	25-27-21 W4	Drumheller	733883	Midland-Tolman
Blue Bride Composite	51°19'N; 112°52'W	22-27-21 W4	Drumheller	696875	Midland-Tolman
Mile 74.0	51°19'N; 112°54'W	21-27-21 W4	Drumheller	671863	Tolman-Carbon
Rosebud	51°19'N; 112°54'W	21-27-21 W4	Drumheller	645857	Carbon
C.P.O.G. Strathmore 7-12-25-25 W4 core	51°07'N; 112°54'W	12-25-25 W4	Strathmore	347650	Bearpaw-East Coulee-Hoodoo-Midland-Tolman

Southeast-northwest Kneehills Creek Transect. Approximately 30 km. along structural dip and across depositional strike.

Outcrop Core	Latitude; Longitude	Section Township Range	1:50 000 NTS Sheet	NTS Grid Location	Stratigraphic Interval
Dunphy Cemetery	51°29'N; 112°51'W	14-29-21 W4	Drumheller	713051	Midland-Tolman
Dunphy	51°29'N; 112°52'W	15-29-21 W4	Drumheller	703046	Midland
Range Rd 21-4	51°28'N; 112°54'W	16-29-21 W4	Drumheller	679040	Midland-Tolman
Range Rd 21-5	51°28'N; 112°56'W	17-29-21 W4	Drumheller	660042	Midland-Tolman
Hesketh	51°28'N; 112°58'W	12-29-22 W4	Drumheller	633042	Midland-Tolman
Horseshoe Canyon	51°26'N; 112°53'W	15-28-21 W4	Drumheller	691992	Tolman-Carbon-Battle
Horseshoe Canyon West	51°25'N; 112°58'W	25-28-22 W4	Drumheller	635985	Carbon-Battle-Scollard
Carbon Gas Plant	51°29'N; 113°02'W	16-29-22 W4	Carbon	590049	Tolman-Carbon
Appleyard Coulee	51°28'N; 113°02'W	9-29-22 W4	Carbon	583028	Tolman-Carbon
Weismer's RR Cut	51°29'N; 113°05'W	18-29-22 W4	Carbon	548051	Tolman-Carbon
Carbon East	51°29'N; 113°07'W	13-29-23 W4	Carbon	530048	Carbon
Carbon West	51°29'N; 113°12'W	17-29-23 W4	Carbon	468058	Carbon-Battle-Scollard
Highway 21RR Cut	51°29'N; 113°14'W	18-29-23 W4	Carbon	446064	Scollard
Three Hills Creek	51°34'N; 113°05'W	17-30-22 W4	Three Hills	562146	Tolman-Carbon



Measured section locations.



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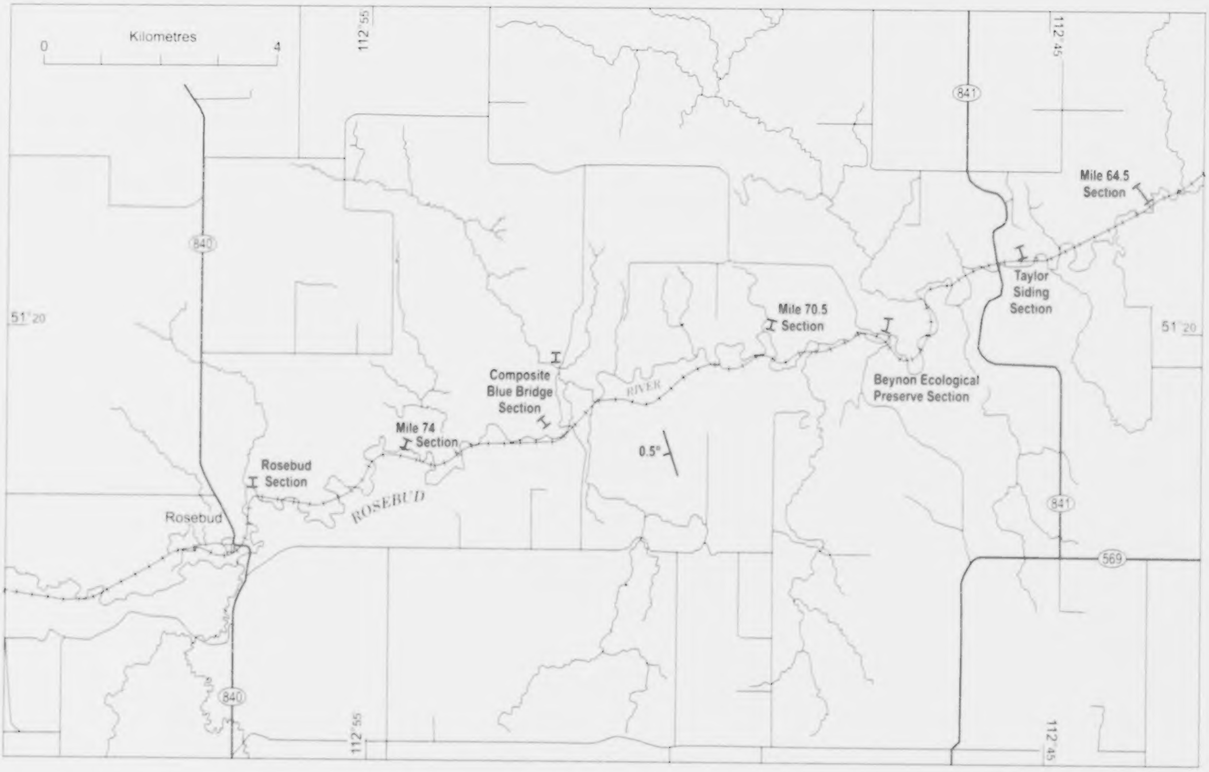

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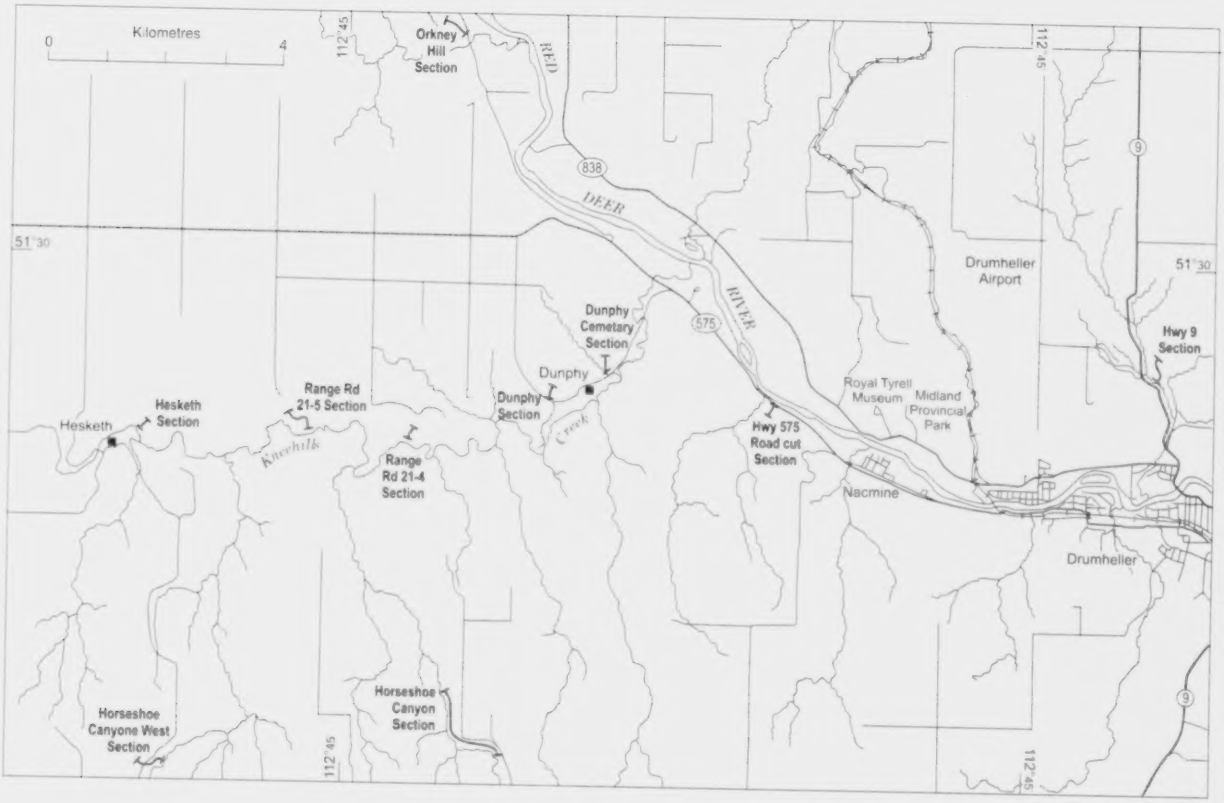

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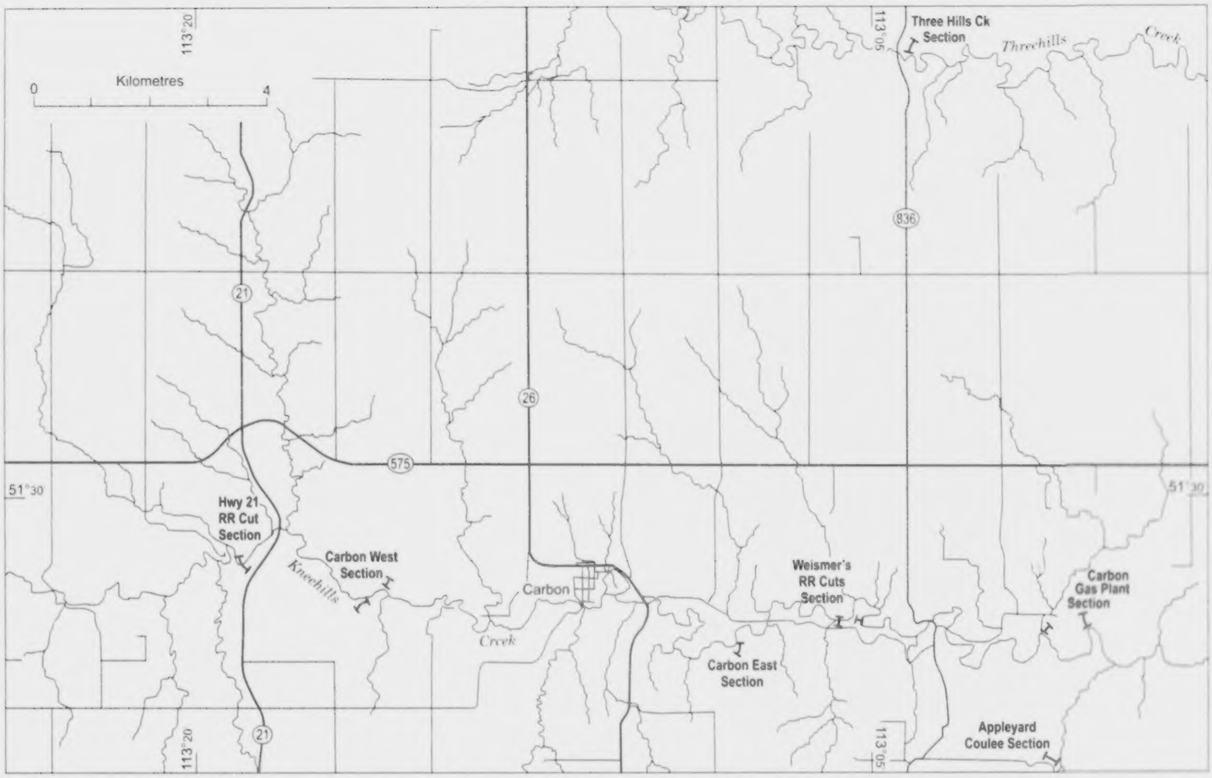

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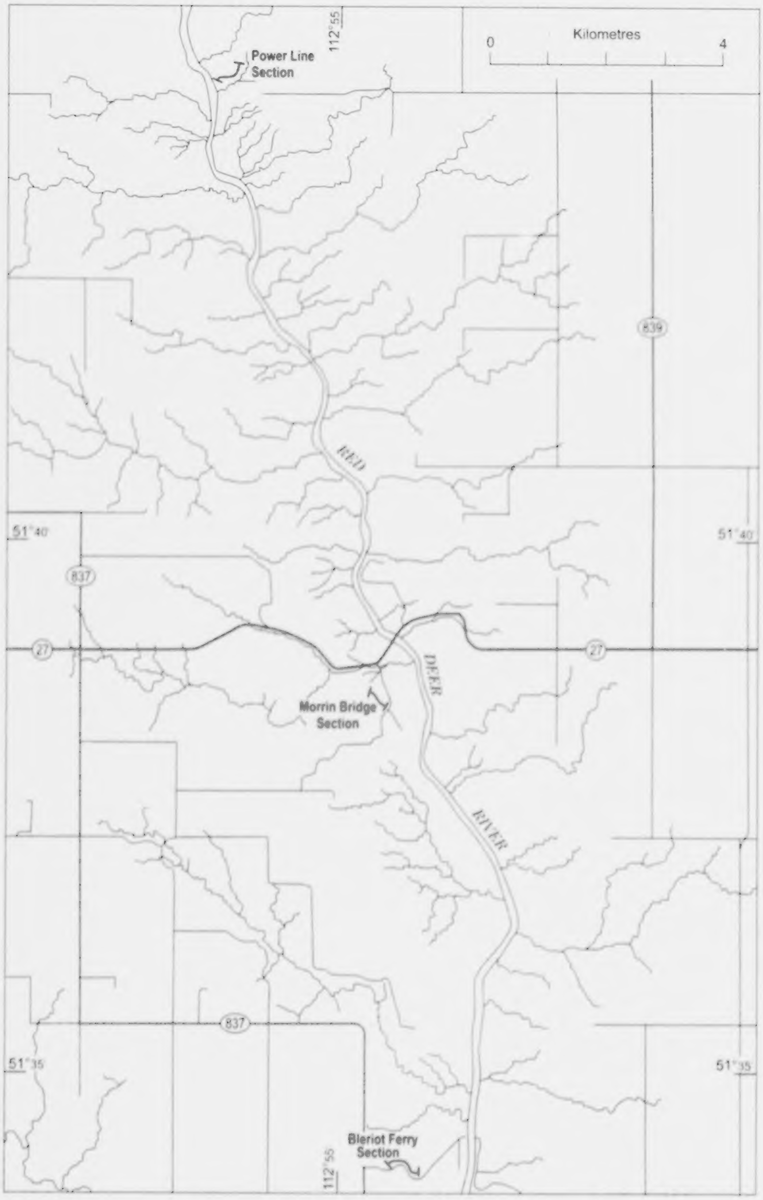

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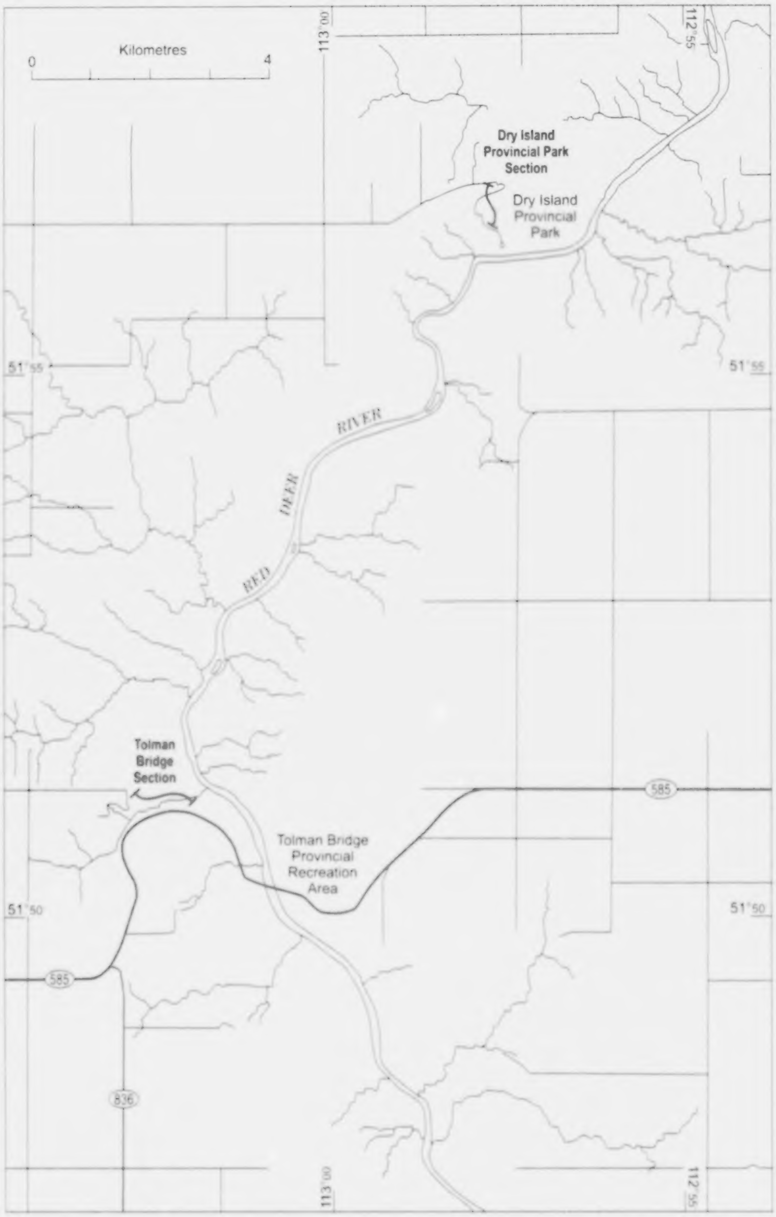
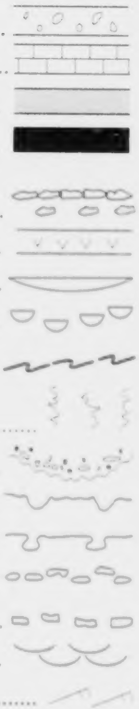

Kilometres
0
4
113°00
112°55
Dry Island Provincial Park Section
Dry Island Provincial Park
51°55
51°55
RED DEER RIVER
Tolman Bridge Section
585
Tolman Bridge Provincial Recreation Area
51°50
51°50
585
836
113°00
112°55

Measured section locations.

LEGEND for Appendix A



Conglomerate

Limestone / dolomitic limestone

Carbonaceous shale

Coal

Siderite concretion bed or calcrete concretions

Bentonite bed

Lens-shaped bed

Discontinuous scour / gutter fills

Fault

Fractures with slickensides (either structural or pedogenic)

Erosive base with rip-ups and granules

Scoured base

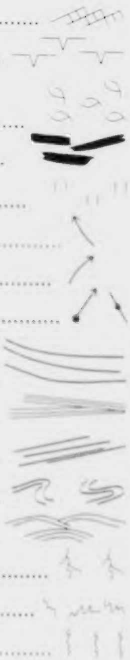
Ball and pillow

Rip-up intraclasts

Breccia / flat-pebble conglomerate

Trough crossbedding

Ripple crosslamination



Climbing ripples

Desiccation cracks

Fossil shells (pelecypod, gastropod, brachiopod)

Carbonized wood fragments

Pedogenic siltstone

Fining-upward trend

Coarsening-upward trend

Paleocurrent indicators

Inclined bedding surfaces (IBS) or lateral accretion surfaces (LA)

Low-angle lamination

Planar tabular crossbedding

Contorted lamination

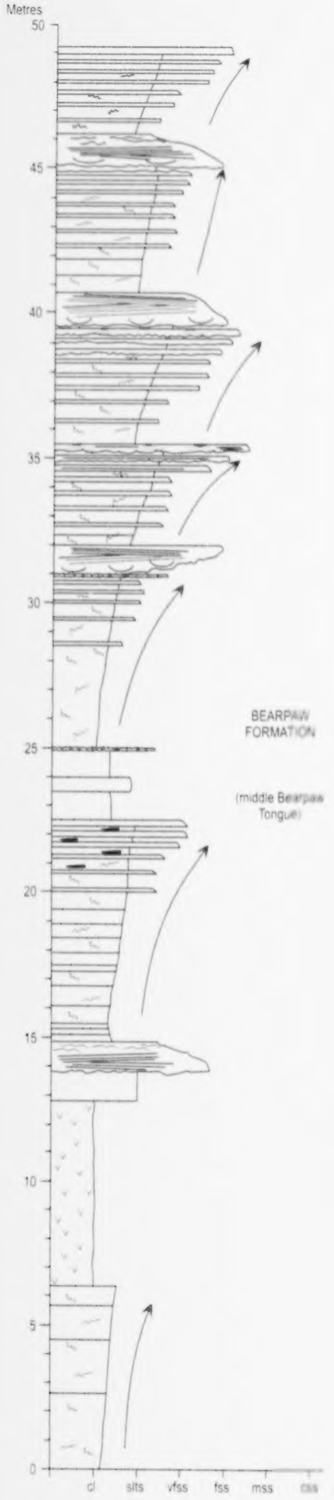
Hummocky cross-stratification (HCS)

Roots

Bioturbation / burrowing

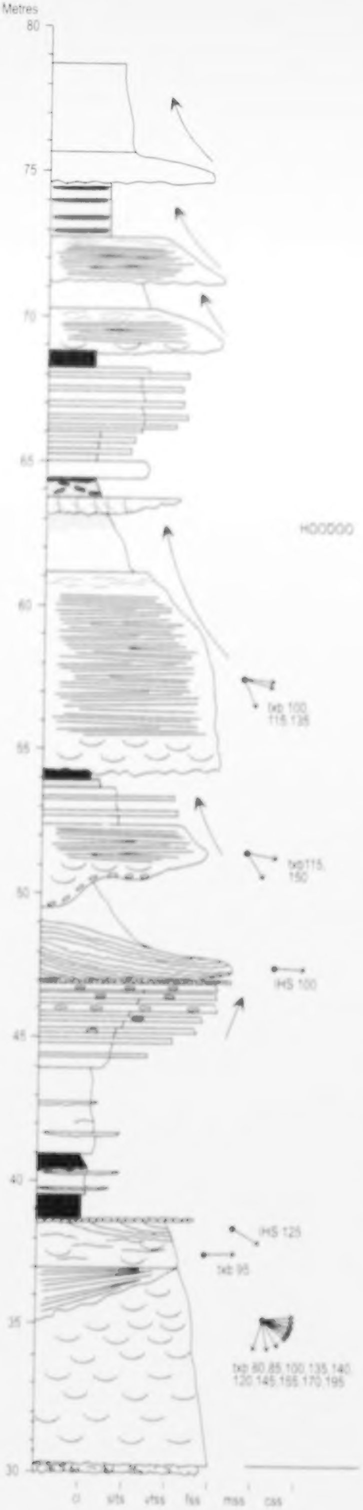
Vertical burrows (e.g. ***Skolithos****)*

West Dorthy Section



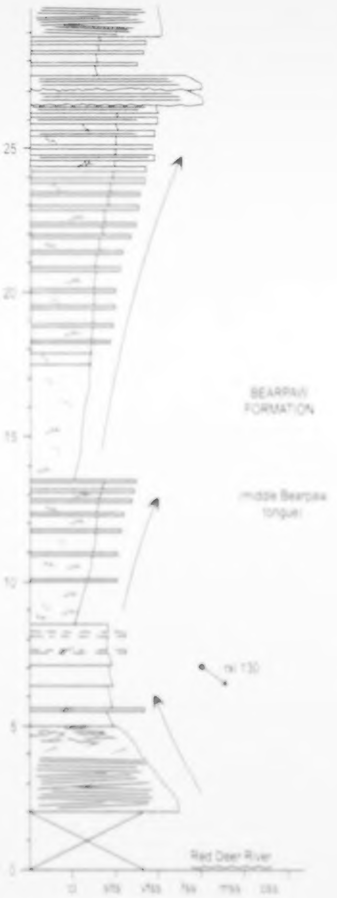
- pale grey fine-grained ss, sharp base and gradational top, low-angle lamination
- thinly interbedded brownish bioturbated slts and grey very fine-grained ss, slightly c-up sequence
- pale grey fine-grained ss, sharp base and gradational top, with few thin silty partings, minor bb, low-angle lamination
- c-up sequence of thinly interbedded brownish bioturbated slts and grey silty very fine-grained ss, ss beds have sharp bases and tops, upper ss has HCS?
- c-up sequence of thinly interbedded brownish bioturbated slts and grey silty very fine-grained ss, ss beds well sorted with sharp bases and tops, upper ss bed is 25 cm fine-medium ss with horizontal lamination and HCS
- pale grey fine-grained ss, lens shaped and pinches out over 50 m laterally, sharp base and top, minor bb, mostly low-angle lamination
- brownish grey silty mudstone, uniform and capped by thin sideritic bed, only thin slts beds near top (present at E Coulee Bridge), bioturbated
- brownish grey silty mudstone, rusty weathering, thin sideritic bed at top
- grey muddy slts, poorly exposed
- brownish grey silty mudstone, poorly exposed
- c-up sequence of brownish grey silty mudstone, to slts and slts to very fine-grained ss, ss beds have sharp bases and gradational tops, horizontal lamination, are up to 25 cm thick at top, ss:slts = 1:5 at base, 1:1 at top, few coaly streaks near top, bioturbation
- brownish grey silty mudstone with very few thin slts beds slts:cl = 1:10, bioturbated
- brownish thinly inter bedded clayey slts and thin slts beds, slts:cl = 1:5
- light grey very fine- to fine-grained ss sharp base with minor scour topography, low-angle lamination, gradational top with silty interbeds
- light grey slts, very uniform
- pale grey weathering, dark brownish grey very bentonitic claystone, sharp base and top, is a very thick bentonite bed (very distinctive white band in hills around Dorothy)
- brownish grey silty mudstone, very few silty bands, sharp top, bioturbated

East Coulee Bridge Section



- grey sandy slts, f-up
- pale grey fine-grained ss, f-up, sharp base, low-angle lamination
- dark grey to black carbonaceous shale, with coaly streaks
- pale grey fine-grained ss, f-up, sharp base, low-angle lamination
- grey sandy slts
- pale grey fine-grained ss, f-up, sharp base and gradational top, minor txb, low-angle lamination
- coal
- thinly interbedded grey sandy slts and silty very fine-grained ss
- thinly interbedded dark grey slts and carbonaceous shale
- grey sandy slts
- dark grey to black carbonaceous shale, coaly at top, wood fragments, laminated
- grey very fine-grained ss, lens shaped, slightly erosional base, roots right through
- brownish grey slts to carbonaceous shale, poorly exposed
- pale grey very fine- to fine-grained ss, slightly f-up to sandy slts, sharp scoured base with minor topography and ?burrows?, uniform, minor txb, mostly low-angle lamination
- grey to rusty grey muddy slts, several 10-20 cm pale grey very fine-grained ss beds in middle, capped by carbonaceous shale and coal
- pale grey fine-grained ss, well sorted, sharp erosional base with up to 1 m topography, sharp top, some txb and mostly low-angle lamination
- f-up muddy channel, lower 1 m is thinly interbedded very fine-grained ss and slts in IHS beds, upper 2 m is primarily brownish grey slts
- c-up sequence of thinly interbedded silty mudstone to slts and very fine- to fine-grained ss, capped by thin siderite bed, ss are sharp based f-up, up to 20 cm thick, have rip-ups and coaly fragments, ss:slts = 1:3 at base, 2:1 at top
- brownish grey silty mudstone, uniform, very few discontinuous very fine-grained ss lenses
- carbonaceous shale to coal, sharp top
- grey to dark grey silty mudstone, carbonaceous at base, few thin lenses of very fine-grained ss
- coal, bituminous, gradational top
- whitish grey fine-grained ss, well sorted, sharp flat base and sharp flat top at base of next siderite, castellated hoodoo forms, slightly f-up, mostly txb, near top is deep and wide mud filled channel 2 m deep x 50 m wide, upper part more silty and has IHS beds as wells as txb
- prominent 10 cm siderite band with sharp irregular base and sharp flat top

East Coulee Bridge Section cont.



- whitish grey silty very fine-grained ss, well sorted, sharp base and top, low-angle lamination

- brownish grey silty claystone, with thin sandy slts beds with sharp boundaries, few thin siderite bands (base of section at Hoodoos)

- 2 white fine-grained ss beds, each with sharp base and sideritic band at base, well sorted, laminated

- thinly interbedded brownish grey silty claystone to slts and sandy slts to very fine-grained ss, c-up; ss:slts = 1:3 at base, 1:1 at top; ss beds have sharp bases and tops, [illegible] are laterally continuous and have horizontal lamination; Ophiomorpha and other burrows

- brownish grey silty claystone, no coarser bands, bituminous (midway up Dorothy section) (base of Hoodoos section)

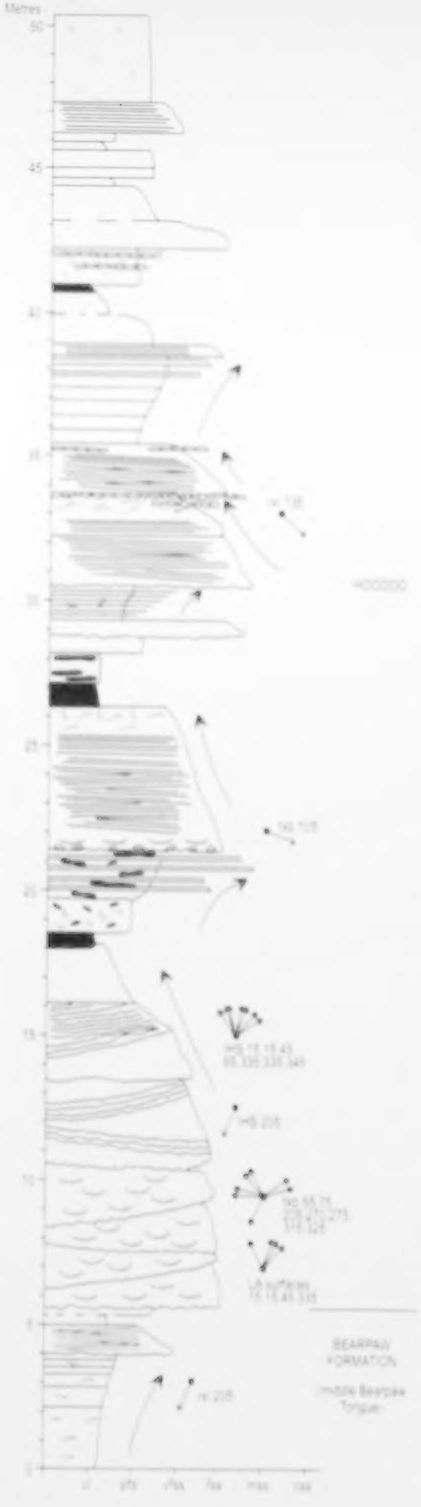
- brownish grey silty claystone to slts, with interbedded thin paler grey slts beds which have sharp sideritized bases and tops; Ophiomorpha; ss:slts = 1:5; c-up

- brownish grey claystone, silty, no coarser bands; Ophiomorpha?

brownish grey thin bedded shaly slts with lesser silty very fine-grained ss; ss:slts = 1:5; few partings of carbonaceous matter; ss are sideritized, parallel-laminted, 1-5 cm, with gradational boundaries

whitish grey fine- to very fine-grained ss, well sorted, thin laminated, low-angle lamination, sharp base, f-up, silty and rxl near top

Hoodoos Section

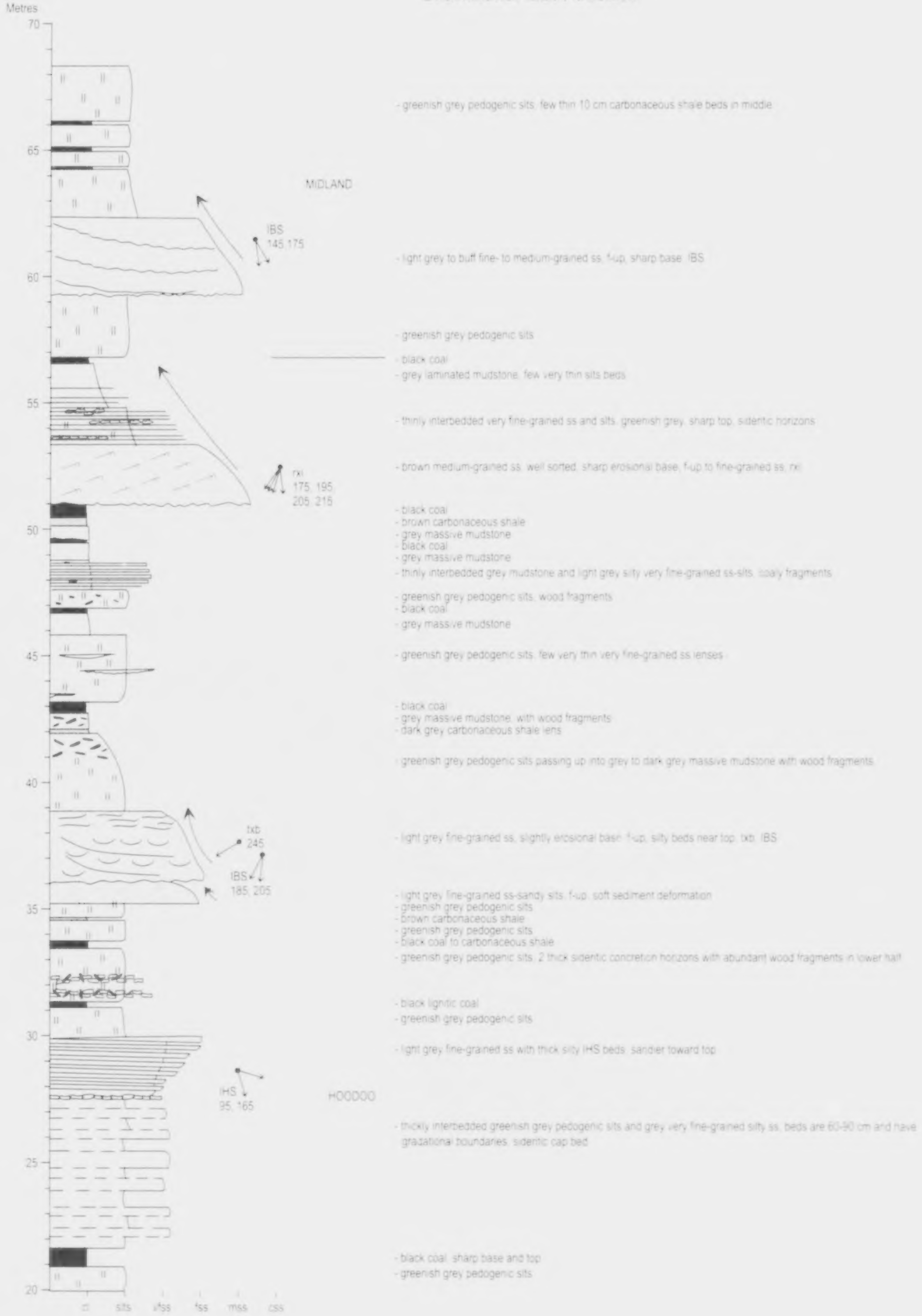


- greenish grey slightly sandy slts. massive. blocky. pedogenic
- pale grey very fine-grained ss. sharp base. gradational top. horizontal lamination
- grey silty shale. uniform. sharp base and top
- dark grey carbonaceous shale
- grey sandy slts. sharp base and top
- dark grey carbonaceous shale
- grey sandy slts. gradational base. sharp top
- pale grey fine- to very fine-grained ss. f-up. sharp base. gradational top
- greenish grey slts. massive. blocky. pedogenic. sideritic concretion horizons near top
- dark grey carbonaceous shale passing up into coal. sharp base. gradational top
- grey sandy slts
- f-up seq from brownish grey sandy slts to pale grey fine-grained ss. well sorted with sharp base and top. horizontal to low-angle lamination
- pale grey fine-grained ss. f-up. sharp flat base. low-angle lamination. several sideritic horizons near top
- grey fine- to very fine-grained ss. slightly f-up. silty at top with rcl. cap of 2 thin siderite horizons
- grey to buff f-mss. sharp flat base. top. low-angle lamination
- thinly interbedded f-up sequence of very fine ss and slts. ss:slts = 1:5. ss have sharp bases and tops. horizontal lamination and rcl. with burrows. slts are organic rich
- pale grey to greenish fine- to medium-grained ss. friable. poorly sorted. silty. sharp base and top
- dark grey slightly carbonaceous slts
- dark grey to black carbonaceous shale. coaly streaks
- coal. black. slightly shaly. vitreous streaks (correlate to lower part of Aerial)
- pale grey fine-grained ss. uniform. well sorted. sharp base with txb and sideritic horizon. sideritic horizons common near base. horizontal to low-angle laminated. rcl at top and roots (present at Wayne 0.5m)
- thinly interbedded sandy slts and fine- to medium-grained ss. gradational base. sharp top. sideritic. abundant large carbonized wood fragments and coaly streaks
- greenish grey slts. abundant carbonized wood fragments. roots? tiny shell fragments
- coal
- grey to dark grey carbonaceous slts. slightly sandy. slightly f-up. gradational base. more carbonaceous up
- pale grey fine-grained ss. well sorted. with several sets of gently dipping IHS. generally f-up to silty very fine-grained ss. and upper 2 m is single IHS set of 5-10 cm ss/slts interbeds
- pale grey fine-grained ss. well sorted. uniform. sharp erosional base with minor topography. sideritized txb horizon at base and several other sideritic horizons near base. likely all

txb. and large sweeping LA surfaces

- grey silty very fine-grained ss
- brownish grey muddy slts. gradational boundaries
- pale grey silty very fine-grained ss. sharp base. gradational top. low-angle lamination. sideritic horizons

Drumheller East Section


Metres
70
65
60
55
50
45
40
35
30
25
20
MIDLAND
IBS
145,175
rxl
175, 195
205, 215
txb
245
IBS
185, 205
IHS
95, 165
HOODOO
cl
sits
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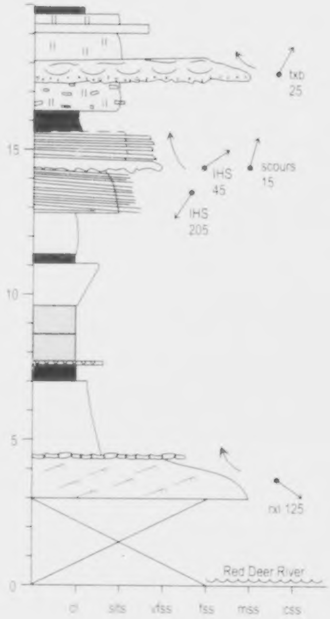
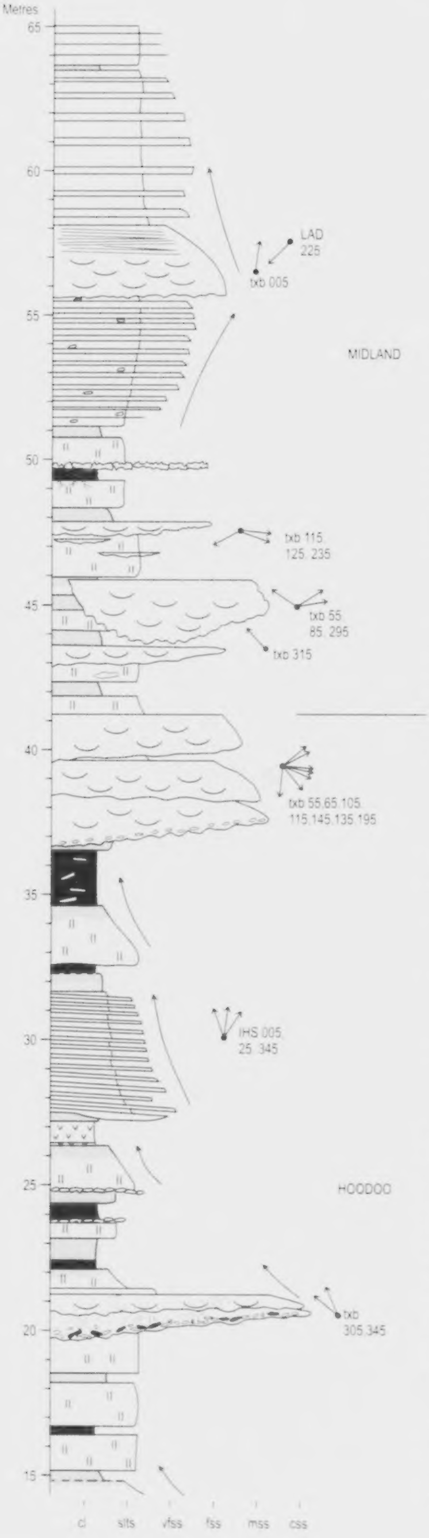
css
- greenish grey pedogenic sits, few thin 10 cm carbonaceous shale beds in middle
- light grey to buff fine- to medium-grained ss, f-up, sharp base, IBS
- greenish grey pedogenic sits
- black coal
- grey laminated mudstone, few very thin sits beds
- thinly interbedded very fine-grained ss and sits, greenish grey, sharp top, sideritic horizons
- brown medium-grained ss, well sorted, sharp erosional base, f-up to fine-grained ss, rxl
- black coal
- brown carbonaceous shale
- grey massive mudstone
- black coal
- grey massive mudstone
- thinly interbedded grey mudstone and light grey silty very fine-grained ss-sits, coaly fragments
- greenish grey pedogenic sits, wood fragments
- black coal
- grey massive mudstone
- greenish grey pedogenic sits, few very thin very fine-grained ss lenses
- black coal
- grey massive mudstone, with wood fragments
- dark grey carbonaceous shale lens
- greenish grey pedogenic sits passing up into grey to dark grey massive mudstone with wood fragments
- light grey fine-grained ss, slightly erosional base, f-up, silty beds near top, txb, IBS
- light grey fine-grained ss-sandy sits, f-up, soft sediment deformation
- greenish grey pedogenic sits
- brown carbonaceous shale
- greenish grey pedogenic sits
- black coal to carbonaceous shale
- greenish grey pedogenic sits, 2 thick sideritic concretion horizons with abundant wood fragments in lower half
- black lignitic coal
- greenish grey pedogenic sits
- light grey fine-grained ss with thick silty IHS beds, sandier toward top
- thickly interbedded greenish grey pedogenic sits and grey very fine-grained silty ss, beds are 60-90 cm and have gradational boundaries, sideritic cap bed
- black coal, sharp base and top
- greenish grey pedogenic sits

Drumheller East Section cont.



- brownish grey carbonaceous shale lens, pinches out laterally
- greenish grey pedogenic slts
- light grey very fine-grained ss, silty, gradational boundaries
- greenish grey pedogenic slts
- light grey fine-medium-grained ss, f-up, erosional base, lag of coarse-grained ss-granule stone, silty beds near top, txb
- greenish grey pedogenic slts, sideritic concretions
- black coal, shalier upward, sharp top
- light grey very fine-grained ss, with inclined slts beds in IHS lamination, gradational top, small erosional scours on base
- brownish grey thinly interbedded very fine-grained ss and slts, in inclined IHS lamination
- grey massive mudstone
- black coal
- grey silty mudstone, sandy at top
- brown mudstone, carbonaceous shale
- dark grey organic rich mudstone, massive
- lignitic coal, pass up to carbonaceous shale, sharp base and top, thin bentonite at top
- grey uniform silty shale
- buff grey medium-grained ss f-up to very fine-grained ss, rxl, 20 cm sideritic horizon at top

Highway #9 Roadcut, North Drumheller



- thickly interbedded greenish grey pedogenic slts and pale grey very fine- to fine-grained ss, minor thin coal

- pale grey very fine- to fine-grained ss, well sorted, sharp flat base, sharp top, low-angle, txb

- c-up sequence of interbedded greenish grey slts and pale grey very fine- to fine-grained ss, many small sideritic concretions throughout

- dark brownish grey carbonaceous mudstone, sharp top, gradational base
- greenish grey pedogenic muddy slts
- rusty sideritic horizon, sharp irregular top
- black bituminous coal, sharp base, roots
- greenish grey pedogenic muddy slts

- brownish grey carbonaceous mudstone, silty
- pale grey fine-grained ss, lens-shaped, txb
- greenish grey pedogenic slts, few sandy lenses near top

- interbedded brown carbonaceous mudstone and greenish grey pedogenic slts, all cut out to N by thick medium-grained ss channel

- pale grey fine-grained ss, well sorted, erosive base, lens shape, txb
- greenish grey pedogenic slts, large flat sideritic concretion
- dark grey carbonaceous mudstone, sharp base and top
- greenish grey pedogenic slts

- pale grey to buff fine- to medium-grained ss, well sorted, slightly f-up, multistoried, erosional channel base with large and small calcrete nodules, txb

- brown carbonaceous mudstone, cut out to N

- black bituminous coal, very uniform, large abundant wood fragments

- greenish grey pedogenic muddy slts, f-up, more carbonaceous upward

- brownish grey carbonaceous mudstone, f-up to black lignitic coal, roots, sharp top

- interbedded greenish grey silty shale and grey shale and minor pale grey sandy slts, erosive base indicates channel form, all bedding inclined, very bentonitic

- brownish grey carbonaceous mudstone, cut out to N
- grey pure claystone, very uniform, bentonitic, massive, featureless, sharp boundaries
- pale greenish while claystone, bentonite
- greenish grey pedogenic slts, f-up to brownish more carbonaceous mudstone

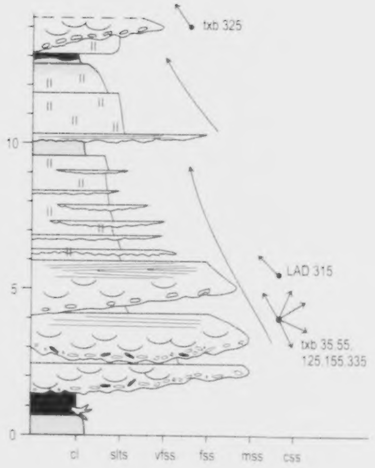
- brownish grey carbonaceous silty mudstone, capped by thin sideritic concretion horizon
- black bituminous coal, more coaly upward, sideritic concretions at base
- greenish grey pedogenic silty mudstone
- brownish grey carbonaceous mudstone
- black lignitic coal, muddy, gradational base, sharp top
- dark greenish grey pedogenic muddy slts, with pale grey very fine-grained ss at base

- pale grey to white medium- to coarse-grained ss, well sorted, slightly f-up, 2 storey, pinches out to S and N over tens of metres, lower storey coarser with large of rip- ups/wood/sideritic nodules and has contorted lamination, upper storey contorted lamination and txb
- greenish grey pedogenic slts, massive, blocky, uniform, thin more carbonaceous bed in middle

- black lignitic coal, muddy
- greenish grey pedogenic slts

- dark brown carbonaceous mudstone
- dark rusty brown silty carbonaceous mudstone, f-up, silty

Highway #9 Roadcut, North Drumheller cont.



- pale grey very fine-grained ss, erosional base with rip-ups, f-up, gradational top, txb
- greenish grey pedogenic slts, cut out by overlying ss
- dark grey carbonaceous mudstone grading up into black lignitic coal, gradational base, sharp top
- darker greenish grey pedogenic silty mudstone, bentonitic, f-up

- greenish grey pedogenic slts, massive, uniform, blocky

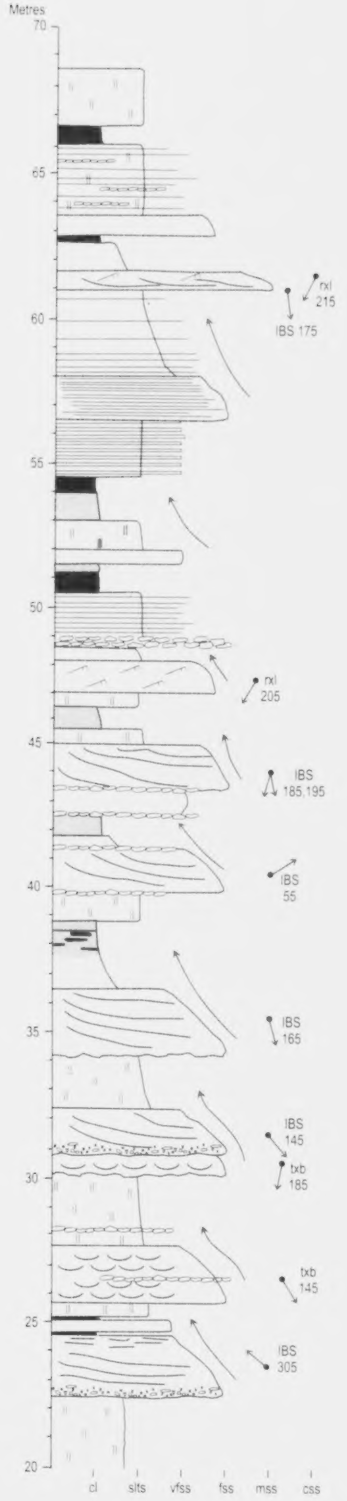
- pale grey fine-grained ss, erosional base, lens shaped, low-angle
- brownish grey carbonaceous mudstone, gradational base, sharp top

- greenish grey pedogenic slts, thin sandy lenses, f-up, gradational boundaries

- pale grey f-mss, well sorted, multistoried, channel scour base with coaly rip-ups and sideritic concretions, f-up, txb, some low-angle lamination, channel complex 40 m across x 5m thick, ss units grade out laterally into slts

- black bituminous coal, sharp base and top, large wood fragments, tree stump, vertical fractures
- brown, rusty weathering carbonaceous mudstone

Drumheller South Section



- greenish grey pedogenic slts

- black coal

- greenish grey slts with many thin very fine-grained ss and sideritic horizons, pedogenic

- greenish grey shaly slts
- pale grey medium-grained ss, sharp base and top, IBS, rxl

- greenish grey slts with many thin very fine-grained ss beds, generally f-up

- grey fine-grained ss, scoured base, gradational top, horizontal lamination

- thinly interbedded greenish grey slts and very fine ss, beds 30 cm, ss:slts = 1:2

- black coal
- dark grey carbonaceous shale

- greenish grey pedogenic slts
- pale grey very fine-grained ss, poorly exposed

- thinly interbedded very fine-grained silty ss and greenish slts, ss:slts = 1:2

- pale grey very fine- to fine-grained ss, sharp flat base and top, rxl

- pale grey to white very fine-grained ss, well sorted, IBS

MIDLAND - brownish grey carbonaceous shale

- pale grey very fine- to fine-grained ss, well sorted, IBS, large sideritic concretions at top

- grey to brownish grey silty shale, generally f-up and more carbonaceous up, several thin discontinuous lenses of coal up to 3 cm thick

- light grey fine-grained ss, well sorted, uniform, sharp scoury base, IBS

- greenish grey slts, uniform, blocky, sharp base and top

- pale grey fine-grained ss, well sorted, uniform, scoured base, multistoried, at base of 2nd storey has lag of large coaly fragments/sideritic concretions/wood fragments, txb in lower part, IBS in upper part

- greenish grey slts, massive, uniform, rubbly, uniform, one 10 cm horizon sideritic concretions in lower part

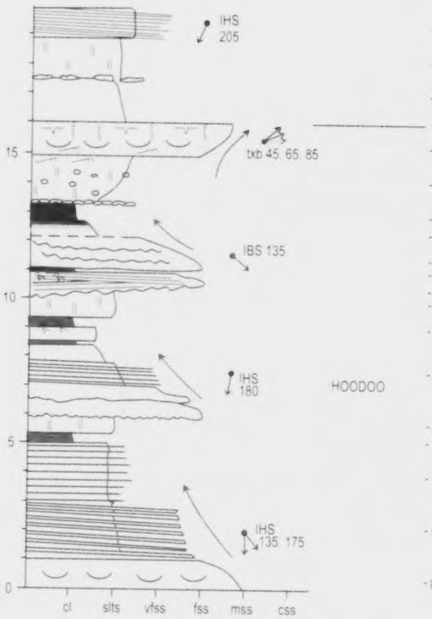
- light grey to white fine ss, sharp flat base, slightly f-up, gradational top, horizon sideritic concretions in middle, large txb

- greenish grey sandy slts, pedogenic, sideritic concretions
- dark grey carbonaceous shale, gradational base, lens-shaped
- light grey silty very fine-grained ss

- light grey fine-grained ss, well sorted, sharp flat base with lag of wood/bone/grit/sideritic concretions, f-up, gradational top, silty beds and thin carbonaceous shale at top, IBS

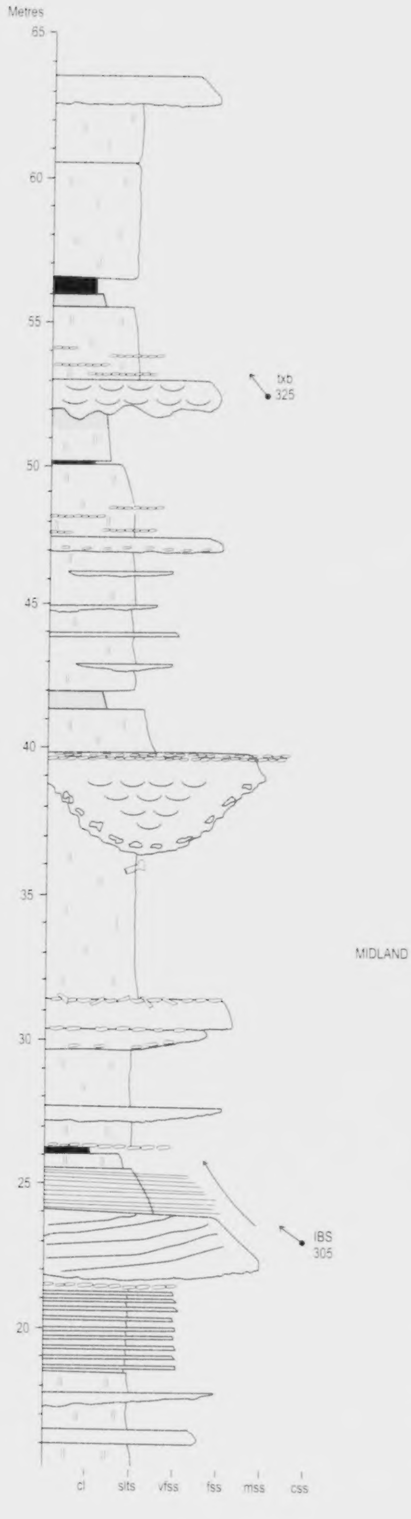
- greenish grey pedogenic slts, massive, uniform, bentonitic

Drumheller South Section cont.



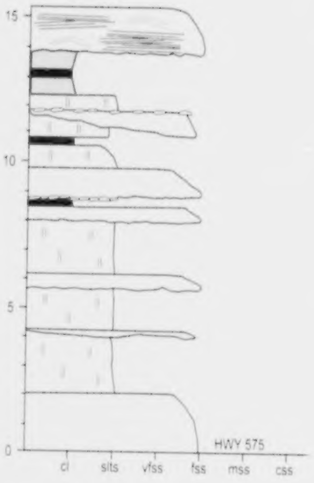
- grey very fine-grained ss-sandy slts, thinly interbedded, gradational top, IHS-like dip
- greenish grey shaly slts, rubbly, pedogenic, sharp base and top
- pale grey to grey slts, slightly f-up, capped by horizon of large sideritic concretions
- brownish grey fine- to medium-grained ss, well sorted, cemented, sharp base with load structures, thin bedded slightly c-up, sharp flat top with *Skolithos* up to 50 cm long, desiccation cracks at top, rxl at base, txb in middle
- greenish grey pedogenic slts, massive, uniform, c-up, blocky, few isolated round calcrete nodules, rxl at top
- black coal, shaly streaks, sharp base and top, sideritic horizon at top
- brownish grey shaly slts, f-up to brown carbonaceous shale
- light grey fine-grained ss, well sorted, few thin silty streaks, gradational top, IBS
- brown carbonaceous shale, sharp base, roots
- light grey fine-grained ss, erosive base, thickens to S, sharp flat top, low-angle lamination
- greenish grey pedogenic slts, massive, uniform
- brown carbonaceous shale, thinly laminated, sharp top, roots
- light grey very fine- to fine-grained ss, multistoried, f-up, upper half has IHS interbedding
- greenish grey pedogenic slts
- dark grey carbonaceous shale
- thinly interbedded greenish grey slts and very fine-grained ss
- rusty grey coloured thinly interbedded fine-grained ss and slts, in IHS lamination
- pale grey fine- to medium-grained ss, no base observed, txb

Highway 575 Roadcut Section



- pale grey fine-grained ss, poorly exposed
- greenish grey pedogenic slts, poorly exposed
- greenish grey pedogenic slts
- black lignitic coal
- brown carbonaceous shale
- greenish grey pedogenic slts, abundant thin sideritic horizons near base
- pale grey fine-grained ss, well sorted, deeply scoured base, txb
- greenish grey pedogenic slts, abundant sideritic horizons near base, thin coal seam in middle, more carbonaceous toward top
- pale grey fine-grained ss, sharp base with sideritic nodule lag
- greenish grey pedogenic slts, with thin very fine-grained ss beds up to 30 cm
- brownish grey more carbonaceous silty shale
- greenish grey pedogenic slts
- pale grey fine- to medium-grained ss, steep-sided channel lens, flat top with thick sideritic horizon
- greenish grey pedogenic slts, uniform, massive, large dinosaur bone near top
- pale grey fine-grained ss, broad lens sharp, capped by sideritic horizon with large wood fragments
- pale grey fine-grained ss, sideritic concretions at base and top, lens-shaped
- greenish grey pedogenic slts, massive, blocky
- pale grey fine-grained ss lens, scoured base
- greenish grey pedogenic slts
- horizon of large sideritic concretions
- black coal
- greenish grey pedogenic slts
- pale grey to white fine- to medium-grained ss, f-up from thick bedded ss to interbedded IHS ss/slts at top, sharp scoured base (prominent on cliff face)
- thinly interbedded very fine-grained ss and slts, capped by 20 cm sideritic concretion horizon
- greenish grey pedogenic slts
- pale grey fine-grained ss, lens-shape, pinches out to E
- greenish grey pedogenic slts
- greenish grey pedogenic slts

Highway 575 Roadcut Section cont.



- brownish grey fine-grained ss, sharp base, flat top, low-angle lamination and HCS(?)

- dark grey carbonaceous shale with coal in middle, sharp flat top

- greenish grey pedogenic slts
- pale grey to white fine-grained ss, sharp scoured base, flat top, pinch out to W, thickens to E, capped by sideritic horizon
- black lignitic coal
- greenish grey pedogenic slts, f-up, more carbonaceous toward top

- pale grey fine-grained ss, poorly exposed
- black lignitic coal capped by 10 cm horizon sideritic concretions
- pale grey to white fine-grained ss, sharp base

- greenish grey pedogenic slts, massive, uniform

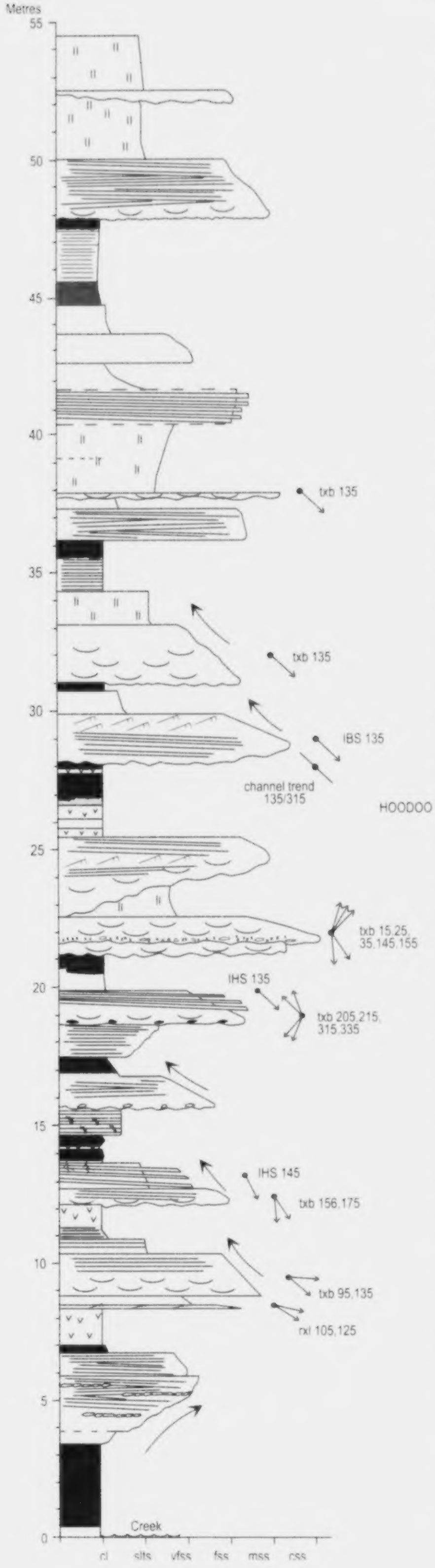
- pale grey to white fine-grained ss, sharp base

- greenish grey pedogenic slts, massive, blocky
- pale grey fine-grained ss, sharp base, pinch out to W

- greenish grey pedogenic slts, massive, uniform, blocky

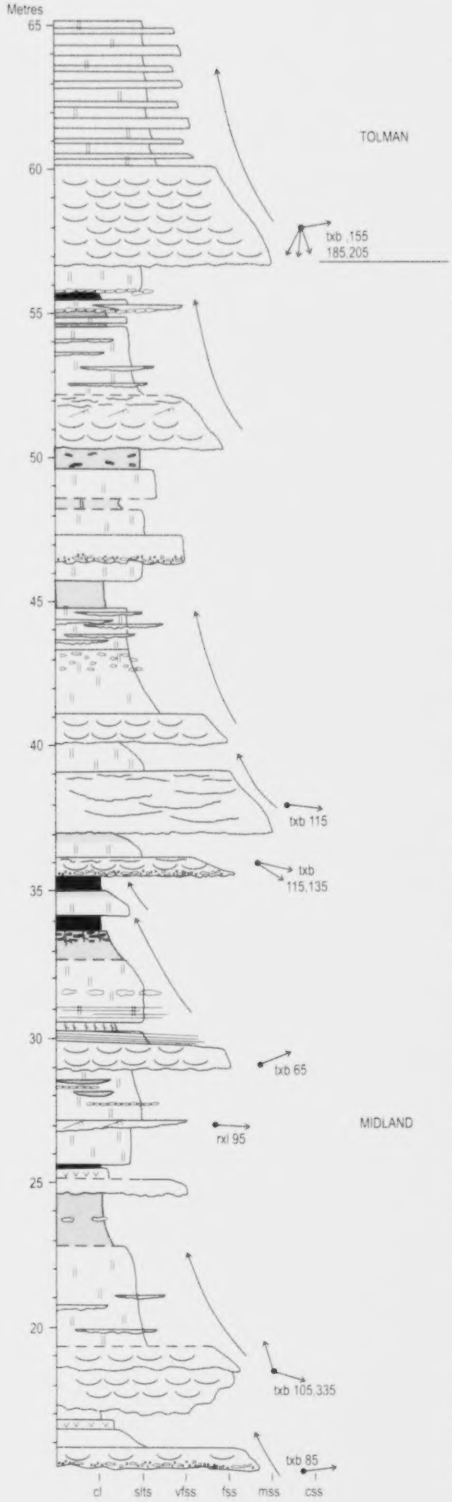
- pale grey fine-grained ss, poorly exposed

Aerial Suspension Bridge Section



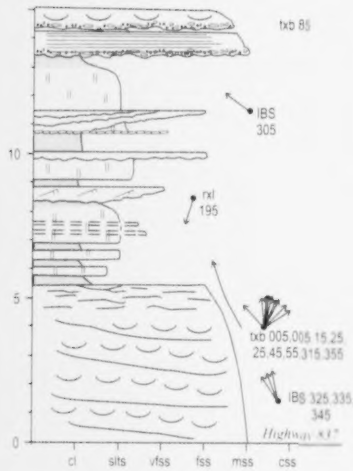
- greenish grey slts, uniform, massive, blocky, pedogenic
- pale grey fine-grained ss, lens-shaped, erosional base, pinches out to SW
- greenish grey slts, uniform, rubbly, blocky, pedogenic
- pale grey to buff fine- to medium-grained ss, well sorted, sharp flat base, minor txb, mostly low-angle lamination
- coal
- grey mudstone, laminated
- dark grey carbonaceous mudstone
- grey mudstone
- pale grey very fine-grained ss, sharp base and top
- grey mudstone
- pale grey fine-grained ss, with silty interbeds, gradational base and top
- greenish grey slts, slightly c-up, uniform, rubbly, pedogenic
- brown fine- to medium-grained ss, erosional base, txb
- dark grey carbonaceous mudstone
- pale grey fine-grained ss, sharp base and top, low-angle lamination
- dark grey carbonaceous shale to coal, gradational base, sharp top
- grey mudstone, uniform, laminated
- greenish grey slts, uniform, blocky, pedogenic
- brownish grey very fine- to fine-grained ss, slightly erosional base, sharp top, sideritic horizon at base, txb
- dark grey carbonaceous shale, sharp top
- greenish grey mudstone, sharp base, gradational top
- pale grey fine- to medium-grained ss, f-up, erosional base, pinches out from base to SW and NE over 100 m, low-angle lamination, rxl at top
- interbedded coal and carbonaceous shale and thin bentonite
- brown mudstone, very bentonitic, abundant wood fragments
- coal and carbonaceous shale
- brown mudstone, very bentonitic
- pale grey fine- to medium-grained ss, well sorted, deeply erosional base cuts out underlying unit to E over 20 m laterally, low-angle lamination, minor txb and rxl
- greenish grey sandy slts, uniform, blocky, pedogenic
- pale grey medium-grained ss, slightly f-up, feldspathic, erosional base, sharp flat top, second erosional surface near base with coarse-grained ss and calcrete nodules, txb
- black coal
- grey to brownish grey mudstone, sharp base, gradational top
- pale grey fine- to fine-grained, f-up, sharp base and top, coaly fragments and txb at base, IHS at top
- grey to greenish grey silty to sandy mudstone, slightly c-up, uniform, bentonitic, laminated
- black coal, lignitic, gradational base, sharp top
- grey to dark grey very fine- to fine-grained ss, sharp erosional base, silty, f-up to gradational top
- brownish grey muddy slts, uniform, laminated, burrowing?
- coal with 20 cm pale grey bentonite in middle
- thinly interbedded grey slts and pale grey very fine-grained ss, IHS, roots at top
- pale grey to white fine-grained ss, sharp erosional base, gradational top, low-angle lamination, minor txb at base
- grey uniform mudstone, very bentonitic, blocky
- dark grey carbonaceous shale, laminated, coaly streaks
- thinly interbedded very fine-grained ss and slts, gradational base, sharp top
- pale grey fine- to medium-grained ss, well sorted, feldspathic, sharp flat base and top, txb at base, horizontal lamination at top
- grey silty very fine-grained ss
- pale grey fine- to medium-grained ss, sharp base and top, rxl
- greenish grey uniform mudstone, very bentonitic
- dark grey carbonaceous shale, laminated, sharp base and top
- pale grey very fine- to fine-grained ss, sharp base and top, low-angle lamination
- pale grey very fine- to fine-grained ss, c-up, low-angle lamination, many sideritic horizons
- grey mudstone, slightly c-up, laminated at base, gradational top
- black coal, sharp base and top (near top of Hoodoos section)
- dark grey carbonaceous shale
- grey mudstone, in stream bottom

Orkney Hill Section - Hwy 837 - Red Deer River



- thinly interbedded greenish grey pedogenic slts and very fine-grained ss, few sideritic horizons
- pale grey fine- to medium-grained ss, well sorted, f-up, sharp base and top, txb (prominent white band near top of cliff)
- greenish grey pedogenic sandy slts, sideritic concretions at base
- black coal, muddy
- greenish grey pedogenic slts, few very fine-grained ss lenses, few more carbonaceous zones, one thin sideritic horizon near top
- pale grey fine- to very fine-grained ss, well sorted, f-up, sharp flat base with large sideritic concretions, silty partings and more gradational top
- brownish grey slightly carbonaceous slts, scattered carbonized wood fragments
- greenish grey pedogenic slts, 50 cm bed more grey and carbonaceous in middle, sandy at top
- pale grey very fine-grained ss, scour base with lag of large sideritic concretions/wood fragments/granules
- greenish grey pedogenic slts
- brownish grey silty shale, slightly carbonaceous
- interbedded greenish grey pedogenic slts and very fine- to fine-grained ss on 20 cm scale, gradational boundaries, lenses
- greenish grey pedogenic slts, f-up from sandy near base, abundant sideritic concretions near top
- pale grey fine-grained ss, well sorted, f-up
- greenish grey pedogenic slts, f-up, gradational base
- pale grey to white fine- to medium-grained ss, well sorted, scoured base, large-scale low-angle txb, silty partings at top (prominent white band in upper half of cliff)
- greenish grey pedogenic slts, f-up to brownish grey more carbonaceous shale
- pale grey fine-grained ss, f-up, scoured base, sideritic horizons, silty partings at top, txb
- black lignitic coal, muddy
- greenish grey pedogenic slts, f-up to dark grey carbonaceous shale
- black bituminous coal
- brown carbonaceous shale, gradational base, f-up, upper 20 cm very hard with abundant carbonized wood fragments and roots
- greenish grey pedogenic slts, f-up, sandy lenses at base, large isolated sideritic concretion with irregular surfaces in middle
- greenish grey pedogenic silty mudstone, sharp base, gradational top, roots abundant
- pale grey fine-grained ss, well sorted, sharp scoured base, f-up, silty partings at top with IHS, txb
- greenish grey pedogenic slts, sandy, few thin sideritic horizons, few more carbonaceous horizons
- pale grey very fine-grained ss, rxl
- greenish grey pedogenic slts
- dark grey carbonaceous shale
- pale grey to white bentonite, massive, gradational base and top
- pale grey very fine-grained ss, sharp base, gradational top
- brownish grey carbonaceous shale, lenses of greenish grey sandy slts, large isolated sideritic concretions in middle
- greenish grey sandy pedogenic slts, f-up, gradational top, few very fine-grained ss lenses
- pale grey fine-grained ss, sharp scoured base, multistoried, pinches out to N over 10 m, txb, f-up to gradational top
- dark grey carbonaceous shale, lens shape pinches out to E
- yellowish white silty bentonite, massive, sharp base and top
- grey silty mudstone, fairly gradational base, sharp top
- pale grey to buff fine- to medium-grained ss, well sorted, multistoried with thin silty lenses separating 3 stories, sideritic horizons mark sharp scoured bases, horizontal lamination, txb

Orkney Hill Section - Hwy 837 - Red Deer River cont.



- greenish grey pedogenic slts, sharp base and top, f-up to brown slightly carbonaceous shale at top

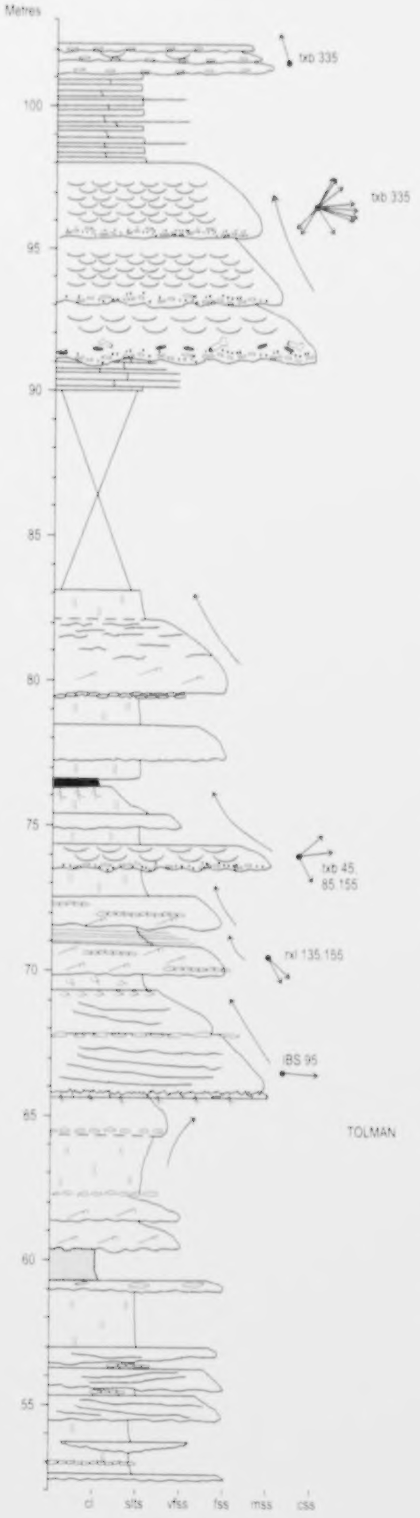
- pale grey fine-grained ss, well sorted, lens-shaped, downcuts to N over 15 m, IBS
- greenish grey pedogenic slts
- dark grey carbonaceous shale, cap of sideritic concretions
- greenish grey sandy pedogenic slts
- pale grey very fine-grained ss, sharp based lens gradational top
- dark grey carbonaceous shale
- pale grey very fine-grained ss, well sorted, lens-shaped, pinches out over 10 m, sharp base and top, rxl

- greenish grey pedogenic sandy slts, f-up to greyer more carbonaceous shale, sideritic sandy zones with gradational boundaries near base

- thinly interbedded dark grey organic-rich carbonaceous shale with lamination and rxl, and greenish grey shaly pedogenic slts

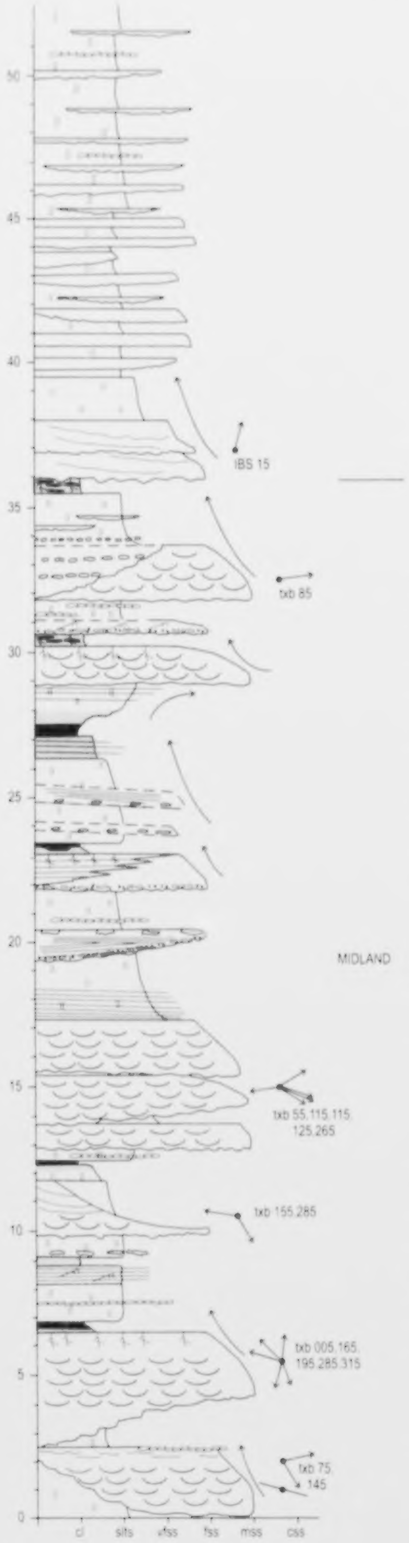
- pale grey fine- to medium-grained ss, well sorted, f-up, fairly sharp top, few silty partings at top, txb, IBS, small slts filled scour at top surface

Bleriot Ferry Section - Red Deer River, West Side



- grey medium-grained ss, well sorted, multistoried, thin bedded, sharp bases with rip-ups, low-angle lamination, txb
- thinly interbedded grey siltstone and grey mudstone with few thin very fine-grained ss and sideritic concretions
- yellow brown medium- to coarse-grained ss, well sorted, very feldspathic, sharp channel scour base with rip-ups of siltstone/granules/coaly fragments/dinosaur bones, multistoried, txb
- thinly interbedded greenish grey siltstone and pale grey very fine-grained ss and grey mudstone
- greenish grey pedogenic siltstone, massive, uniform
- pale grey fine-grained ss, well sorted, f-up, sharp base, gradational top, silty interbeds, rxl
- greenish grey pedogenic siltstone, capped by thin sideritic horizon
- pale grey fine-grained ss, well sorted, f-up
- greenish grey pedogenic siltstone
- black carbonaceous shale to coal
- greenish grey pedogenic siltstone f-up to more carbonaceous rooted silty mudstone
- pale grey very fine-grained ss, sharp base and top
- greenish grey pedogenic siltstone
- pale grey fine- to medium-grained ss, well sorted, f-up, scoured base with large sideritic concretions, sharp top, txb
- greenish grey pedogenic siltstone
- pale grey fine-grained ss, multistoried, 2 units separated by thin siltstone lens, many thin sideritic horizons, IHS? in middle
- greenish grey sandy siltstone, few scattered large oyster shells
- pale grey fine-to medium-grained ss, well sorted, f-up, IBS, capped by thin horizon broken oyster shells in sandy siltstone
- pale grey fine-medium ss, well sorted, f-up, IBS, cap of large sideritic concretions
- pale grey fine ss, f-up, well sorted, gradational base with distinct sideritic bed, very sharp and irregular top with sideritic/cemented medium ss with vertical fractures and roots
- greenish grey pedogenic sandy siltstone, massive, uniform
- pale grey very fine-grained ss, scoured base, f-up to si, rxl, cap of sideritic concretions
- pale grey very fine-grained ss, scoured base, f-up to si, rxl
- brownish grey slightly carbonaceous mudstone, sharp base and top
- white fine-grained ss, sharp base and top, large isolated sideritic concretions
- greenish grey pedogenic siltstone, massive, uniform, blocky
- pale grey fine-grained ss, well sorted, multistoried, units separated by thin greenish grey siltstone lenses with sideritic concretion horizons, IBS

Bleriot Ferry Section - Red Deer River, West Side cont.



- interbedded greenish grey pedogenic siltstone, pale grey very fine- to fine-grained ss, generally f-up, beds 50-100 cm, lens shaped, few thin sideritic horizons

- greenish grey pedogenic siltstone, sandy, massive, uniform

- rusty coloured grey fine-grained ss, f-up, multistoried, scoured base, sharp top, IBS

- dark grey carbonaceous shale with coaly partings, sharp base and top, roots throughout

- greenish grey pedogenic siltstone, uniform, massive, small white calcrete nodules near base, few thin very fine-grained ss lenses

- pale grey fine-medium ss, well sorted, f-up sharp base and top, txb cut out to W by overlying slts which is dark rusty coloured with sideritic horizons
- greenish grey pedogenic shaly siltstone, 2 distinct sideritic horizons
- buff to grey fine-grained ss, sharp base with coaly rip-ups, gradational top
- brown carbonaceous shale, coaly partings, rootlets
- pale grey to white fine- to medium-grained ss, well sorted, slightly f-up, sharp base, all txb, large roots at top

- greenish grey pedogenic sandy siltstone c-up, thin brownish carbonaceous shale at base, more sandy beds toward top

- black coal, muddy, sharp base, gradational top, less coaly upward
- brownish grey carbonaceous siltstone, shaly, few thin sandy lenses, inclined lamination

- thickly interbedded greenish grey pedogenic siltstone and pale grey very fine-to fine-grained ss, gradational boundaries, appear to be inclined bedding (IHS?), lens shapes, large coaly rip-ups

- brown carbonaceous shale passing up and laterally to black lignitic coal
- pale grey very fine- to fine-grained silty ss, f-up, sharp base with sideritic rip-ups, grades upward and laterally to muddy slightly carbonaceous siltstone with low angle lamination (IHS?), roots
- greenish grey to rusty weathering pedogenic siltstone, horizon sideritic concretion near base

- pale grey to white fine-grained ss, sharp based, f-up, well sorted, lens shaped, sideritic rip-ups, capped by large isolated sideritic concretions, low-angle lamination

- pale greenish grey pedogenic sandy siltstone, f-up, IHS-like bedding

- pale grey fine- to medium-grained ss, well sorted, multistoried separated by slts lenses, txb (most prominent ss)

- rusty coloured sandy siltstone, sideritic horizons
- greenish grey pedogenic siltstone, finer and more carbonaceous upward

- pale grey fine-grained ss, well sorted, slightly f-up, sharp flat base with small scours, cut out to E by shale-filled scour, txb at base, IBS at top

- greenish grey pedogenic siltstone, uniform, blocky, large isolated sideritic concretions near base
- brown carbonaceous shale
- thinly interbedded greenish grey pedogenic siltstone and pale grey very fine ss, ss:slts = 1:1, rxl
- greenish grey pedogenic siltstone, thin sideritic horizon in middle

- dark brown carbonaceous shale f-up to black coal

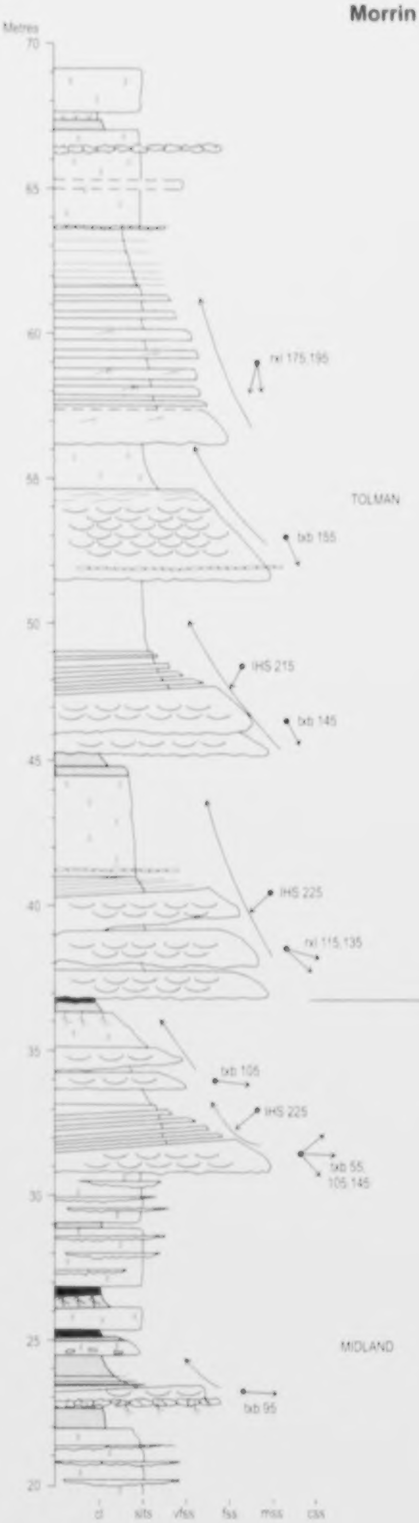
- pale grey fine- to medium-grained ss, well sorted, f-up, channel scour cuts down to W, roots at top

- grey silty shale, massive, cut out to W by overlying ss

- pale grey fine- to medium-grained ss, well sorted, scoured channel base, thins out laterally with steep side, silty partings, sharp top, sideritic horizons near top, abundant txb

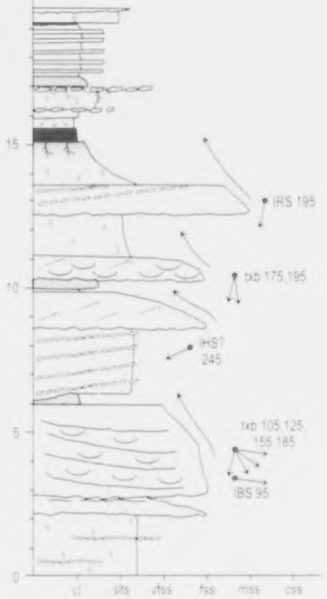
- greenish grey pedogenic siltstone

Morrin Bridge Section - Red Deer River, West Side



- greenish grey pedogenic slts
- white claystone; bentonite sharp top
- brownish grey carbonaceous mudstone
- rusty coloured sideritic concretion horizon, sharp irregular top
- greenish grey pedogenic slts, thin sandy streak in middle
- thinly interbedded rusty coloured very fine-grained ss and slts, cap of sideritic concretions
- interbedded greenish grey pedogenic slts and pale grey very fine- to fine-grained ss on 30-50 cm scale, gradational boundaries, rxl
- greenish grey pedogenic slts, gradational base sharp top
- pale grey fine-grained ss, sharp base, gradational top, rxl
- greenish grey pedogenic slts, gradational base
- pale grey to white fine- to medium-grained ss, well sorted, slightly f-up, sharp flat base, sideritic near base, txb
- greenish grey sandy slts, gradational base, sharp top
- pale grey fine- to medium-grained ss, well sorted, multistoried, sharp base, gradational top, inclined silty interbeds and sideritic horizons
- dark grey carbonaceous mudstone, gradational base, sharp top
- greenish grey pedogenic slts, f-up to more carbonaceous slts at top, one sideritic horizon at base
- pale grey to white fine- to medium-grained ss, well sorted, multistoried separated by thin slts lenses and sideritic concretion horizons, inclined IHS beds at top
- dark grey carbonaceous mudstone, gradational base, sharp top, f-up, coaly at top
- greenish grey sandy slts, pedogenic, f-up, massive, uniform, roots
- pale grey fine-grained ss, well sorted, multistoried, separated by thin slts lens with sideritic concretions, txb
- greenish grey sandy slts, f-up
- pale grey to dark grey fine- to medium-grained ss, f-up, IHS unit, primarily interbedded inclined fine-grained ss and sandy slts with few thin sideritic horizons, sharp base, txb
- greenish grey pedogenic slts, many thin sandy lenses, few sideritic horizons, one thin carbonaceous mudstone in middle
- grey carbonaceous mudstone grading up into black coal, sharp top, roots, flattened wood fragments
- greenish grey pedogenic slts
- dark grey carbonaceous shale to coal
- greenish grey pedogenic slts, more carbonaceous upward, sideritic concretions at base
- grey to brownish grey slightly carbonaceous mudstone, silty interbeds, sharp top
- pale grey very fine- to fine-grained ss, well sorted, lens-shape pinches out to W, txb
- horizon of large sideritic concretions with slickensides, fractures, roots
- brownish grey carbonaceous mudstone, few grey horizons
- greenish grey pedogenic slts, with broad thin lenses very fine-grained ss up to 5 m across

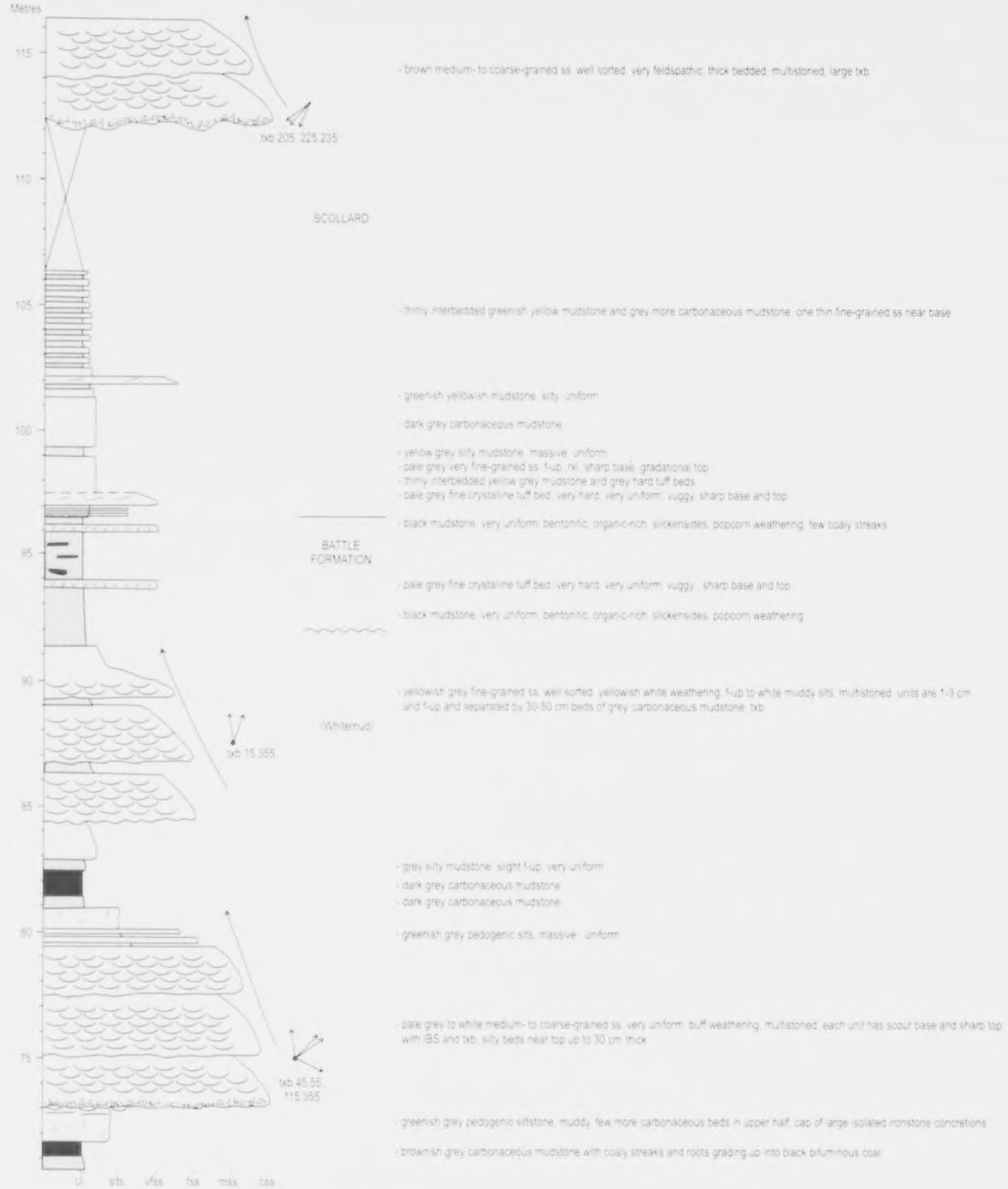
Morrin Bridge Section - Red Deer River, West Side cont.



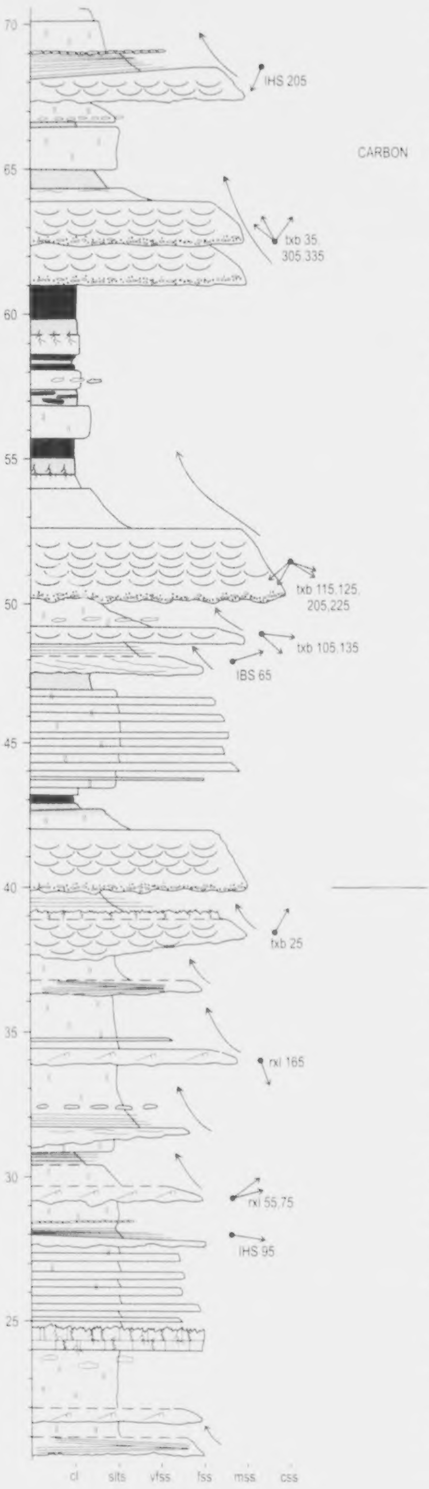
MIDLAND

- thinly interbedded grey slts and brownish carbonaceous mudstone, gradational boundaries, thin coal at top
- greenish grey silty shale overlain by horizon of large sideritic concretions with slickensides and large wood leaf fragments, overlain by carbonaceous shale
- grey mudstone, cap of large sideritic concretions
- white silty claystone, bentonite
- black muddy coal, f-up
- greenish grey pedogenic slts, f-up to grey more carbonaceous slts to brownish grey carbonaceous mudstone, sharp top, roots
- pale grey fine- to medium-grained ss, well sorted, slightly f-up, sharp base, inclined sideritic horizons
- greenish grey pedogenic slts, uniform, massive, blocky
- pale grey fine-grained ss, well sorted, sharp base with large sideritic concretions and coaly rip ups, txb, rxl
- dark grey carbonaceous shale, more brownish and silty upward
- pale grey fine-grained ss, f-up, flat base, upper part is greenish grey slts, rxl
- greenish grey sandy slts, with many inclined sideritic horizons
- dark grey carbonaceous mudstone, pinches out to W, sharp top
- pale grey fine-grained ss, slightly f-up, well sorted, broad shallow scour base, sharp top with roots, IBS, txb
- pale grey fine-grained ss, f-up to silty very fine-grained ss, sharp base
- greenish grey pedogenic sandy slts, few thin horizons siderite

Tolman Bridge Section - Red Deer River, West Side

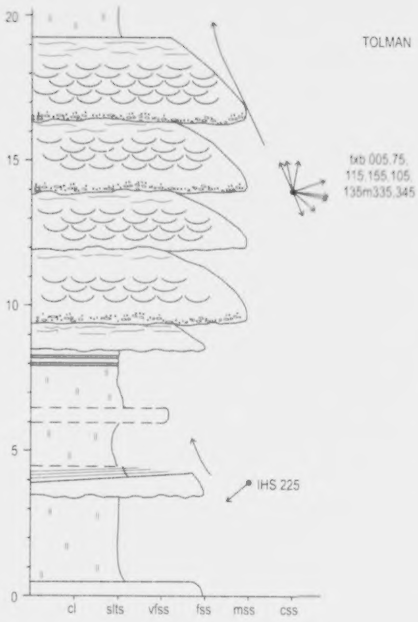

Metres
115
110
105
100
95
90
85
80
75
txb 205. 225 235
- brown medium- to coarse-grained ss. well sorted. very feldspathic. thick bedded. multistoried. large txb
SCOLLARD
- thinly interbedded greenish yellow mudstone and grey more carbonaceous mudstone. one thin fine-grained ss near base
- greenish yellowish mudstone. silty. uniform
- dark grey carbonaceous mudstone
- yellow grey silty mudstone. massive. uniform
- pale grey very fine-grained ss. f-up. rxl. sharp base. gradational top
- thinly interbedded yellow grey mudstone and grey hard tuff beds
- pale grey fine crystalline tuff bed. very hard. very uniform. vuggy. sharp base and top
- black mudstone. very uniform. bentonitic. organic-rich. slickensides. popcorn weathering. few coaly streaks
BATTLE FORMATION
- pale grey fine crystalline tuff bed. very hard. very uniform. vuggy . sharp base and top
- black mudstone. very uniform. bentonitic. organic-rich. slickensides. popcorn weathering
- yellowish grey fine-grained ss. well sorted. yellowish white weathering. f-up to white muddy slts. multistoried. units are 1-3 cm and f-up and separated by 30-50 cm beds of grey carbonaceous mudstone. txb
(Whitemud)
txb 15.355
- grey silty mudstone. slight f-up. very uniform
- dark grey carbonaceous mudstone
- dark grey carbonaceous mudstone
- greenish grey pedogenic slts. massive . uniform
- pale grey to white medium- to coarse-grained ss. very uniform. buff weathering. multistoried. each unit has scour base and sharp top with IBS and txb. silty beds near top up to 30 cm thick
txb 45.55 115.355
- greenish grey pedogenic siltstone. muddy. few more carbonaceous beds in upper half. cap of large isolated ironstone concretions
- brownish grey carbonaceous mudstone with coaly streaks and roots grading up into black bituminous coal
cl
slts
vfss
fss
mss
css

Tolman Bridge Section - Red Deer River, West Side cont.



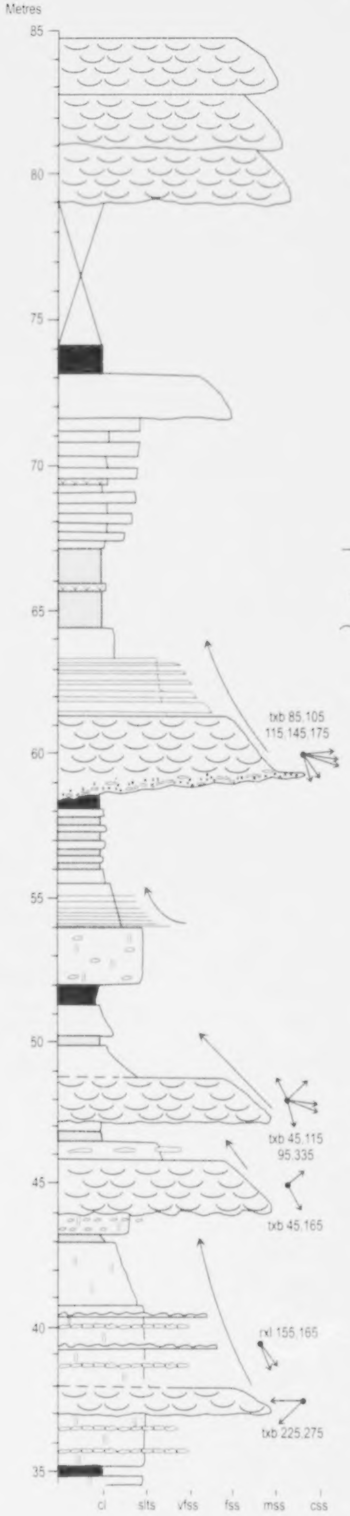
- grey silty mudstone, f-up, more carbonaceous up
- greenish grey pedogenic muddy slts, massive, uniform
- pale grey fine- to medium-grained ss, f-up, buff weathering, scoured base, interbedded ss and slts, IHS at top capped by thin ironstone horizon
- greenish grey pedogenic slts, thin ironstone horizons near base, f-up
- dark grey carbonaceous mudstone
- greenish grey pedogenic slts, massive, uniform
- brownish grey silty mudstone, f-up, mare carbonaceous
- grey sandy siltstone, f-up, few carbonaceous streaks
- pale grey to white medium-grained ss, well sorted, buff weathering, multistoried, sharp base and top, lag of calcrete nodules, txb
- black bituminous coal, muddy streaks
- brown carbonaceous mudstone, gradational boundaries
- grey silty mudstone, gradational tops, roots
- two thin black coal beds separated by brown carbonaceous mudstone
- grey mudstone, one horizon of large scattered ironstone concretions, slickensides and calcite vugs
- brownish grey carbonaceous mudstone, coaly streaks
- grey slightly silty pedogenic mudstone
- brown carbonaceous mudstone with roots and coaly fragments grading up into thick black bituminous coal, sharp top
- grey mudstone, gradational base and top
- greenish grey siltstone f-up to more carbonaceous silty mudstone
- pale grey to white medium- to coarse-grained ss, well sorted, f-up, scoured base with silt rip-ups, LAD, txb, sharp top
- greenish grey silty mudstone, pedogenic, horizon of large ironstone concretions near base, sharp top
- pale grey medium-grained ss, well sorted, sharp base, txb
- grey sandy siltstone with very fine-grained ss beds
- buff weathering fine-grained ss, well sorted, sharp base, f-up, IBS
- brownish grey more carbonaceous silty mudstone
- thickly interbedded greenish grey pedogenic siltstone and buff fine- to medium-grained ss with gradational boundaries, slightly carbonaceous throughout
- grey mudstone
- brown carbonaceous shale grading up into black bituminous coal
- greenish grey pedogenic siltstone, f-up, more brown and carbonaceous upward
- pale grey to white fine- to medium-grained ss, well sorted, scour base with silty rip-ups, all txb
- greenish grey pedogenic sandy siltstone with beds of pale grey fine-grained ss, f-up
- pale grey fine- to medium-grained ss, well sorted, slight f-up, deeply scoured base, txb, cap of sandy ironstone with gradational base and sharp irregular top, vertical fractures and slickensides
- greenish grey pedogenic siltstone, massive, blocky
- pale grey fine-grained ss, sharp base, gradational top, LAD
- greenish grey pedogenic siltstone, numerous small ironstone concretions throughout, one thin fine-grained ss bed near base
- pale grey fine- to medium-grained ss, well sorted, sharp base, rxl
- greenish grey pedogenic siltstone, slight f-up, gradational base, sharp top, horizon of large isolated ironstone concretions near base
- pale grey fine-grained ss, scoured base, thickness to W, silty partings
- thinly interbedded brownish carbonaceous shale and greenish grey silty shale, 1:1
- greenish grey pedogenic siltstone, f-up, gradational base and top
- pale grey fine-grained ss, well sorted, f-up, scoured base, gradational top, all rxl
- greenish grey pedogenic siltstone, horizon of ironstone concretions near base
- pale grey fine-grained ss, well sorted, grading up into thinly interbedded ss and slts, IHS at top, f-up
- thickly interbedded poorly exposed greenish grey pedogenic siltstone and pale grey very fine- to fine-grained ss, ss:slts= 1:1, beds about 50 cm
- rusty weathering greenish grey limestone, sandy, fine crystalline, sharp base, very sharp top with vertical fractures and roots, slickensides
- greenish grey pedogenic siltstone, few large ironstone concretions near top, massive
- pale grey fine-grained ss, gradational boundary, horizontal lamination
- greenish grey pedogenic siltstone, gradational base
- pale grey fine-grained ss, gradational boundaries, horizontal lamination
- greenish grey pedogenic siltstone, massive, uniform, blocky

Tolman Bridge Section - Red Deer River, West Side cont.



- pale grey fine- to medium-grained ss. well sorted. multistoried. thick bedded. each 2 m unit f-up from sharp base with rip-ups to medium-grained ss to silty fine-grained ss with silty bands. caliche nodule rip-ups near top. cemented zones give hoodoo appearance. txb
- pale grey fine-grained ss. f-up. sharp base. silty partings near top
- greenish grey pedogenic siltstone. massive. uniform. several very thin more carbonaceous beds near top
- pale grey silty very fine- to fine-grained ss. silty partings. gradational base and top
- greenish grey pedogenic siltstone
- pale grey fine-grained ss. well sorted. sharp erosional base passing up into interbedded IHS. ss and slts. gradational top
- greenish grey pedogenic siltstone. uniform. blocky. rubbly. massive
- pale grey fine-grained ss

Dry Island Park Section - Red Deer River West Side



- brownish grey to buff to yellowish brown medium- to coarse-grained ss, multistoried, txp

SCOLLARD

- black bituminous coal
- pale grey fine-grained ss, well sorted, f-up, sharp base
- thickly interbedded bright greenish grey mudstone and yellowish grey siltstone, one thin discontinuous white claystone bentonite in middle

BATTLE FORMATION

- dark purplish black mudstone, v. uniform, v. bentonitic, sharp base, in middle is 20 cm discontinuous pale grey bentonitic claystone

- grey silty mudstone, very uniform
- pale grey fine-grained ss, well sorted, f-up to interbedded slts and vfss, bentonitic

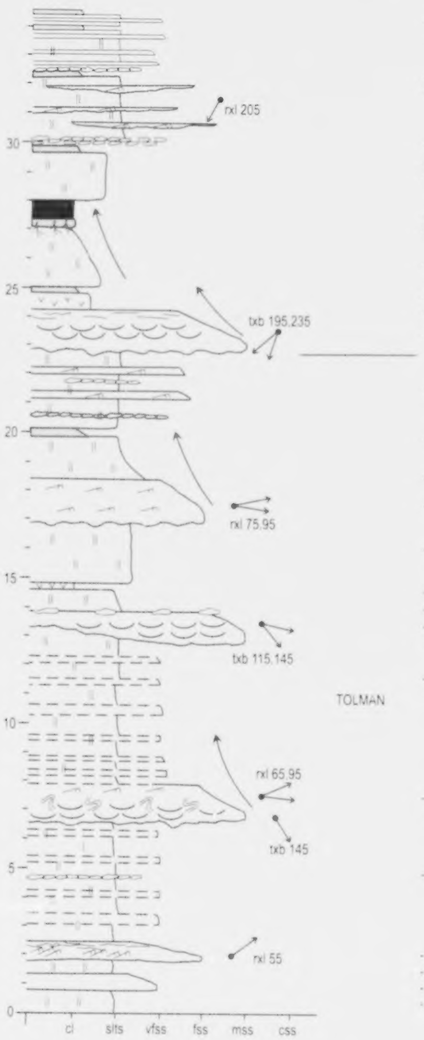
(Whitemud)

- pale grey to white fine- to medium-grained ss, well sorted, slightly f-up, channel scour base with coarse-grained ss grains and many small light grey caliche rip-ups, down-cuts into coal and thickens to SW
- black bituminous coal, sharp base and top, partly cut out by overlying ss
- thickly interbedded pale grey mudstone and dark brownish grey carbonaceous mudstone with roots
- pale grey mudstone, uniform
- thinly interbedded grey mudstone and pale grey very fine- to fine-grained ss, f-up sequence, sharp base, gradational top
- greenish grey pedogenic siltstone, muddy, few scattered ironstone concretions
- black bituminous coal, muddier upward, gradational top
- grey bentonitic mudstone, f-up
- brownish grey carbonaceous mudstone, sharp top
- grey mudstone, slightly silty, f-up
- pale grey fine- to medium-grained ss, well sorted, slight f-up, sharp flat base, slight gradational top, txb
- grey mudstone
- dark grey carbonaceous mudstone, sharp base and top

CARBON

- brownish grey sandy siltstone, slightly carbonaceous, horizon of scattered very large ironstone concretions
- pale grey fine- to medium-grained ss, well-sorted, slightly f-up, scoured base with caliche rip-ups, sharp top, txb
- greenish grey pedogenic siltstone, thin horizons of scattered caliche nodules
- brown carbonate mudstone grading up to black lignitic coal
- pale grey silty mudstone, f-up, very bentonitic, sharp base, gradational top
- greenish grey pedogenic sandy siltstone with numerous laterally continuous thin ironstone horizons, several thin fine-grained ss beds with rxl and straight crested symmetrical ripples, ironstone caliche nodules throughout
- pale grey to buff fine- to medium-grained ss, well sorted, f-up, sharp flat base, slight gradational top, txb
- greenish grey pedogenic sandy siltstone, numerous thin ironstone horizons
- black lignitic coal

Dry Island Park Section - Red Deer River West Side cont.



- thickly interbedded greenish grey pedogenic siltstone and very fine-grained ss beds with gradational bounds, two thin carbonaceous mudstones

- brownish grey carbonaceous mudstone, capped by large ironstone concretions
- thickly interbedded greenish grey pedogenic siltstone and broad lenses of fine- to medium-grained ss with rxl

- ironstone horizon 30 cm
- brownish grey carbonaceous mudstone
- greenish grey pedogenic muddy siltstone, uniform, blocky, massive

- black lignitic coal, muddy partings
- brownish grey carbonaceous mudstone, roots

- greenish grey pedogenic silty mudstone, f-up, very uniform, blocky

- brownish grey carbonaceous mudstone, gradational base, sharp top
- pale grey silty claystone, very bentonitic
- pale grey fine- to medium-grained ss, well sorted, slight f-up, scoured base with rip-ups, txb, silty partings at top

- greenish grey pedogenic siltstone, several thin fine-grained ss beds with rxl, several ironstone concretion beds

- dark brownish grey carbonaceous mudstone, coaly streaks, sharp top

- greenish grey pedogenic siltstone, sandy at base, f-up

- pale grey fine-grained ss, well sorted, f-up, sharp scoured base, thin carbonaceous streaks in middle, rxl

- greenish grey pedogenic sandy siltstone

- white claystone, bentonitic, slightly silty, sharp boundaries
- greenish grey pedogenic sandy siltstone
- pale grey fine- to medium-grained ss, well sorted, lens shaped, thickens to North to 1.2 m, sharp base, more gradational top, capped by horizon of scattered large ironstone concretions up to 1 m across

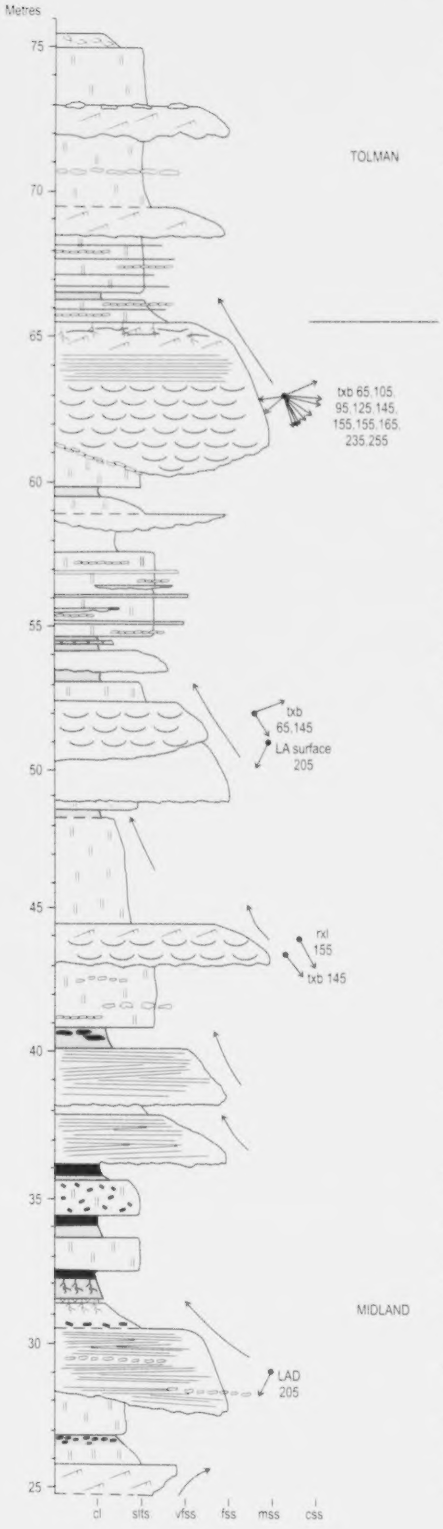
- greenish grey pedogenic siltstone, numerous thin very fine-grained ss beds with gradational bounds up to 30 cm

- pale grey fine- to medium-grained ss, well sorted, slight f-up, sharp base with small scours, gradational top, txb at base, contorted beds in middle, rxl at top

- greenish grey pedogenic siltstone, numerous thin very fine-grained ss beds with gradational boundaries, one thin ironstone horizon in middle

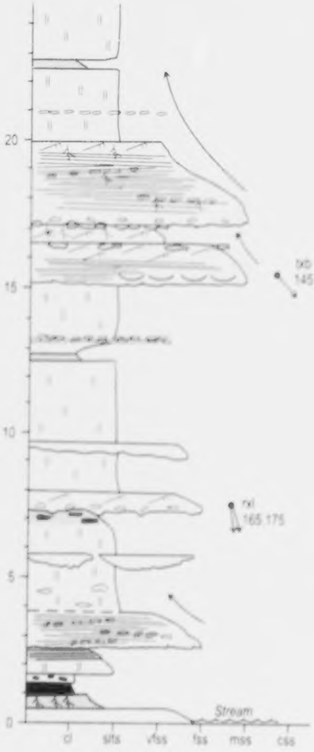
- pale grey fine-grained ss, well sorted, f-up, sharp flat base, climbing ripples
- greenish grey pedogenic siltstone
- pale grey very fine-grained ss, gradational boundaries
- greenish grey pedogenic siltstone, massive, uniform, blocky

Dunphy Cemetary Section - Kneehills Creek



- grey silty mudstone with oyster shells
- pale greenish grey pedogenic slts
- pale grey fine-grained ss, sharp scoured base, capped by large sideritic concretions, rxl
- pale greenish grey pedogenic slts, one horizon large sideritic concretions in middle
- pale grey very fine- to fine-grained ss, sharp base, f-up, gradational top, rxl
- pale greenish grey pedogenic slts, numerous sandy beds and sideritic concretion horizons, one 30 cm carbonaceous shale
- pale grey to buff fine- to medium-grained ss, well sorted, deeply scoured based with topography of up to 1 m, base lined with thin sideritic band, gradational top with silty bands, f-up to gradational top, roots at top, lower 2/3 txb, upper 1/3 horizontal lamination and rxl
- greenish grey pedogenic slts, very bentonitic at base, distinctive 30 cm brownish grey carbonaceous shale with gradational base and sharp top and wood fragments
- pale grey very fine- to fine-grained ss, f-up, sharp scoured base, lens-shape pinches out to N and S over 30 m
- grey shaly slts, uniform, bentonitic
- greenish grey pedogenic sandy slts, numerous very thin very fine-grained ss beds, numerous horizons small sideritic concretions
- 2 thin bands dark grey carbonaceous shale, separated by thin pale grey bentonite
- pale grey very sandy slts, f-up, sharp base
- dark grey carbonaceous shale, sharp top, abundant wood/leaf litter
- greenish grey sandy pedogenic slts, f-up, more carbonaceous upward
- pale grey fine-grained ss, multistoried, sharp flat base, prominent LA surface, txb (prominent white band near top of cliff)
- greenish grey pedogenic slts
- brownish grey carbonaceous shale, gradational base, sharp top
- greenish grey pedogenic slts, very clay-rich, very bentonitic
- pale grey to buff fine- to medium-grained ss, slightly scoured base, well sorted, broadly lens-shaped, txb, rxl
- greenish grey pedogenic sandy slts, several horizons small and large sideritic concretions
- dark brownish grey carbonaceous shale, coaly streaks, sharp top
- multistoried fine-grained ss, white to pale grey, well sorted, 2 stories separated by prominent silty band, sharp bases, low-angle lamination
- black coal with thin carbonaceous slts at base
- greenish grey pedogenic slts, dark colour, abundant tiny wood fragments
- brownish grey carbonaceous shale passing up into bituminous coal, sharp top
- greenish grey pedogenic slts, uniform massive
- black lignitic coal, sharp base and top
- dark grey carbonaceous shale, f-up laminated, roots at top
- greenish grey slts to mudstone, f-up, uniform, wood fragments at base, capped by greenish white bentonite with roots
- pale grey to rusty buff fine-grained ss, well sorted, slightly f-up, thickens to SE/pinches out to NW, gradational top, low-angle lamination, few horizons large sideritic concretions
- greenish grey pedogenic shaly slts, very bentonitic
- greenish grey pedogenic slts, f-up into darker grey more carbonaceous silty shale, sharp top with abundant wood/leaf litter
- pale grey very silty very fine-grained ss, gradational, base, sharp top, rxl

Dunphy Cemetary Section - Kneehills Creek cont.



- greenish grey pedogenic slts. massive, uniform
- dark grey carbonaceous shale, gradational base, sharp top
- greenish grey pedogenic slts, one horizon of sideritic concretions

- pale grey fine-to medium-grained ss. f-up to very fine- to fine-grained ss, well sorted, slightly erosive base with lag of sideritic concretions, few horizons of sideritic concretions with leaves and roots, low-angle lamination

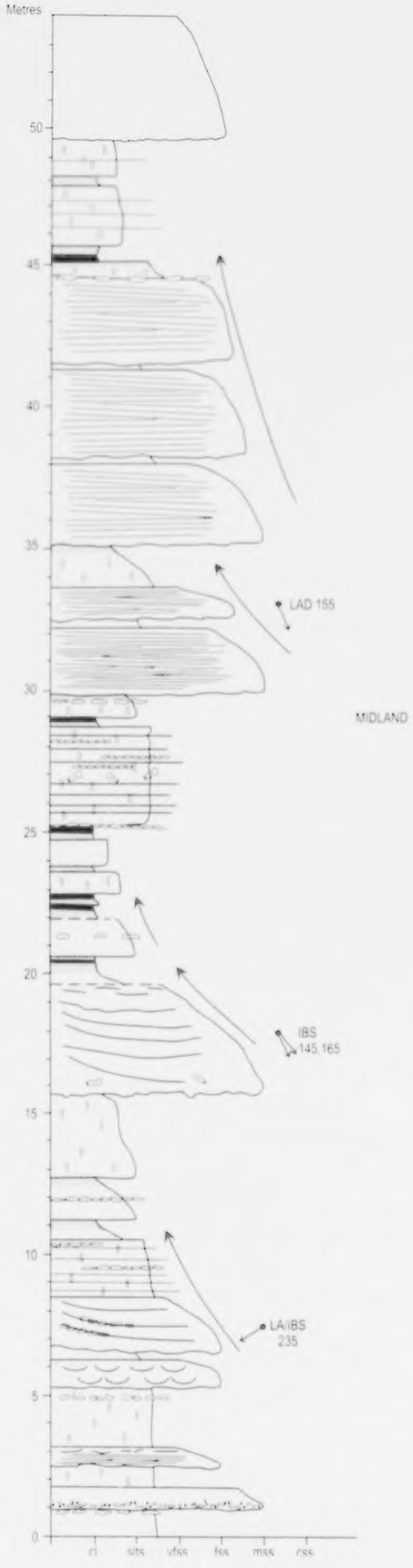
- brownish grey silty very fine-grained ss, uniform, rxl, roots at top, horizon of sideritic concretions at top
- pale grey fine- to medium-grained ss, well sorted, slightly f-up, sharp flat base and top, low-angle lamination and rxl at top several large sideritic concretions at top up to 1 m across
- greenish grey pedogenic slts, uniform, sharp top, prominent sharp-topped horizon of sideritic concretions near base
- dark grey carbonaceous shale, sharp base, more gradational top, abundant wood/leaf litter
- greenish grey pedogenic slts, massive, uniform, rubbly

- lens of pale grey very fine- to fine-grained ss, scour base, pinch out to W over 10 m
- greenish grey pedogenic slts

- pale grey fine-grained ss, sharp base with small scours and lag of sideritic concretions, slightly f-up, sharp flat top, rxl
- greenish grey pedogenic slts, f-up to darker grey more carbonaceous slts-shale with coaly streaks
- scour-based lenses of pale grey fine-grained ss up to 10 m across, separated by slts, sharp flat tops
- greenish grey pedogenic slts, massive, uniform, rubbly, several large sideritic concretions

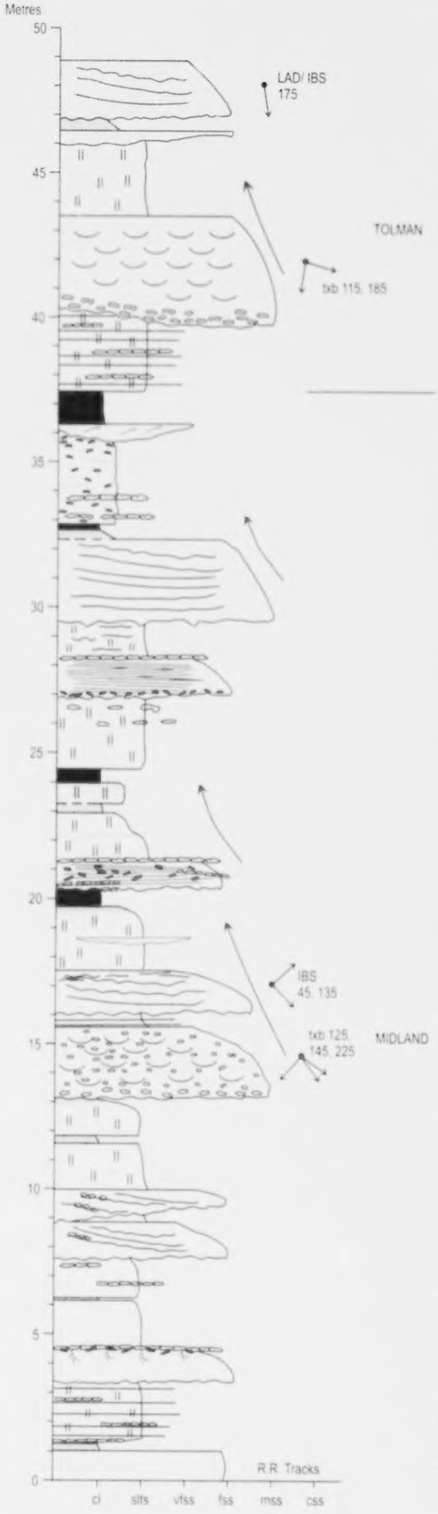
- pale grey to buff fine-grained ss, well sorted, slightly f-up, sharp flat base, gradational top, low-angle lamination horizons of sideritic concretions
- greenish grey pedogenic slts, slightly f-up, more carbonaceous and laminated toward top
- brownish grey carbonaceous shale, plant fragments, gradational top
- black lignitic coal to carbonaceous shale, sharp top
- brownish grey carbonaceous slts-shale, f-up, gradational base, coaly streaks, roots
- pale grey to white fine-grained ss, f-up, well sorted, base not exposed

Dunphy Section - Kneehills Creek



- pale grey fine-grained ss, very poorly exposed
- greenish grey pedogenic muddy slts, pale greenish, uniform, massive, few thin very fine- to fine-grained ss beds, one thin brownish carbonaceous shale in middle
- brownish grey carbonaceous shale, few scattered large sideritic concretions
- black coal
- greenish grey pedogenic slts, slightly carbonaceous upward
- pale grey to white fine- to medium-grained ss, well sorted, multistoried, 3 stories separated by thin silty beds, sharp top capped by large sideritic concretions up to 1 m across
- greenish grey pedogenic slts, f-up to brownish more carbonacenus shale
- pale grey to buff fine- to medium-grained ss, multistorey, 2 stories separated by prominent silty bed, generally f-up, low-angle lamination
- greenish grey pedogenic slts, more carbonaceous and brown toward top, horizon of large sideritic concretions near top
- brown carbonaceous shale f-up to black coal
- greenish grey very sandy pedogenic slts, numerous thin very fine-grained ss beds and several horizons of sideritic concretions especially in upper half, abundant bone fragments and ?skeleton? in middle
- brown carbonaceous shale f-up to black coal, capped by continuous sideritic horizon
- greenish grey massive silty shale, bentonitic
- greenish grey pedogenic slts, shaly, capped by brownish carbonaceous shale
- brown carbonaceous shale, f-up to black coal in 2 sequences
- greenish grey bentonitic silty mudstone, sharp base, gradational top, large sideritic concretion
- dark greenish grey slts, f-up to brownish grey carbonaceous shale, f-up to black coal, capped by dark grey carbonaceous shale
- pale grey to white fine- to medium-grained ss, f-up, sharp base with small scours, gradational top with silty beds, abundant low-angle/IBS, scattered bone fragments
- greenish grey pedogenic slts, slightly f-up to bentonitic muddy silt at top, thin carbonaceous horizon in middle
- dark greenish bentonitic slts, f-up to dark grey carbonaceous shale, sideritic horizon
- dark greenish muddy slts, f-up to dark grey carbonaceous shale, bentonitic, sharp top
- greenish grey pedogenic slts, sandy, numerous very fine-grained ss beds, several horizons sideritic concretions
- pale grey fine-grained ss, multistoried, 2 stories separated by prominent silty band, sharp top, lower 1/3 txb, upper 2/3 has low-angle/IBS and sideritic horizons dipping (prominent white band near base)
- greenish grey pedogenic slts, sandy, horizon of sideritic concretions near top
- pale grey fine-grained ss, sharp flat base, silty beds near gradational top, low-angle lamination
- greenish grey pedogenic sandy slts
- pale grey fine- to medium-grained ss, f-up, sharp base with lag of wood fragments, sharp top
- greenish grey sandy slts, large sideritic concretions at top

Range Rd 21-4 Section - Kneehills Creek



- buff to rusty silty fine-grained ss, f-up, many sideritic horizons, low-angle lamination/IBS

- dark grey carbonaceous shale, gradational top
- pale grey fine-grained ss, sharp base, gradational top

- greenish grey pedogenic slts, massive, uniform

- pale grey fine-medium-grained ss, well sorted, erosive base, cuts down to SE, abundant rip-ups, txb

- greenish grey pedogenic slts, many thin very fine-grained ss beds, many thin sideritic horizons

- black coal

- pale grey very fine-grained ss, lens shape, sharp base, rxl

- grey silty mudstone, few carbonaceous streaks, abundant tiny wood fragments throughout, 2 horizons of very large sideritic concretions near base

- black coal
- brown grey carbonaceous shale, gradational base

- pale grey fine-medium-grained ss, well sorted, slightly f-up, sharp base with minor scours, low-angle lamination/IBS

- greenish grey pedogenic slts, few grey carbonaceous streaks

-pale grey fine-grained ss, well sorted, slightly f-up, sharp base with coaly rip-ups, low-angle, capped by sideritic horizon

- greenish grey pedogenic slts, few horizons large scattered sideritic concretions near top

- black coal
- dark greenish grey muddy slts, carbonaceous
- brown carbonaceous shale, gradational base and top
- greenish grey pedogenic slts, carbonaceous zone in middle, f-up, bentonitic at top

- buff very fine-fine-grained ss, sharp base, numerous sideritic horizons, low-angle lamination, carbonaceous wood fragments, capped by extensive sideritic horizon
- black coal

- greenish grey pedogenic slts, f-up to browner more carbonaceous muddy slts at top, one thin - very fine-grained ss scour lens in middle

- pale grey to white fine-medium-grained ss, multistoried, slightly f-up, 2 stories separated by 50 cm interbedded very fine-grained ss and slts, lower storey has abundant white caliche nodules rip-ups and txb, upper storey is IBS/low-angle lamination

- greenish grey pedogenic slts, f-up to brownish grey carbonaceous shale

- brownish grey carbonaceous shale, sharp top

- greenish grey pedogenic slts, massive, uniform

- pale grey fine-grained ss, multistoried, 2 stories separated by 20 cm slts lens and amalgamate toward W, sharp bases, low-angle/IBS shown by thin dipping sideritic horizons

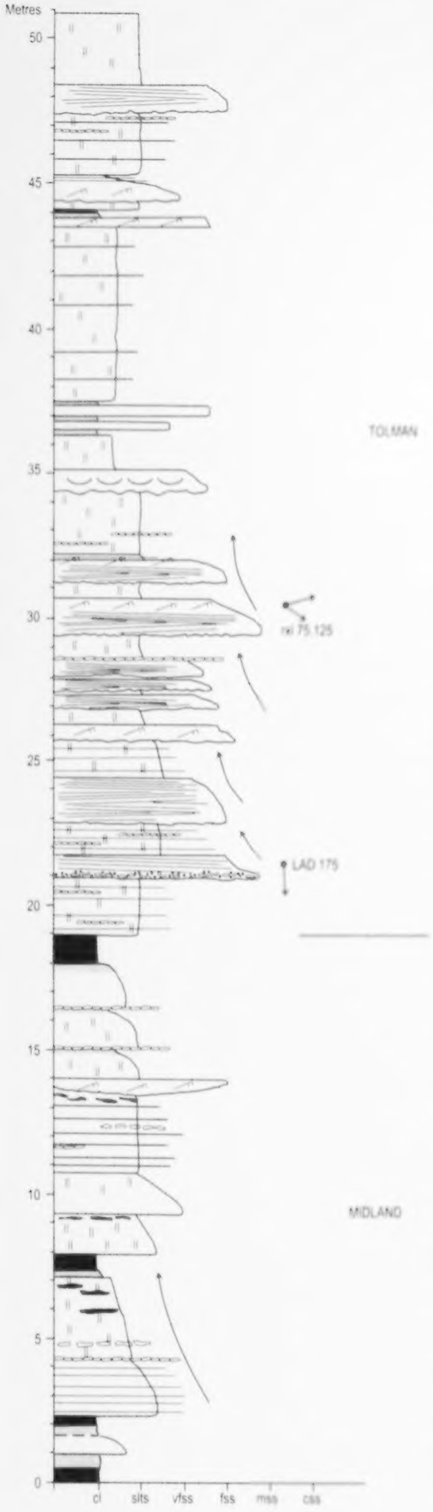
- greenish grey pedogenic slts, uniform, rubbly, several sideritic horizons near top, one very thin carbonaceous zone in middle

-pale grey to white fine-grained ss, well sorted, slightly f-up, sharp base, capped by horizon of large sideritic concretions with roots, and wood fragments

- greenish grey pedogenic slts, numerous thin very fine-grained ss beds, few horizon siderite

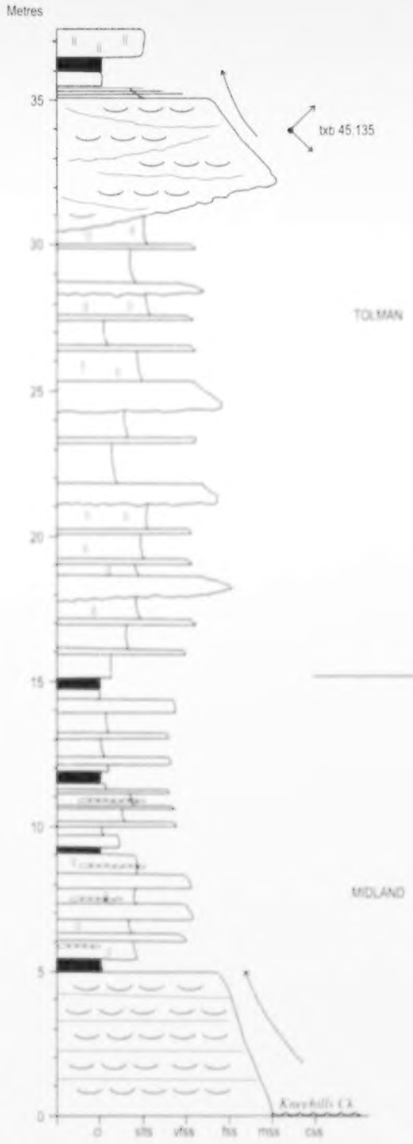
- brownish grey carbonaceous shale, sideritic concretions at top
- pale grey fine-grained ss, poorly exposed

Range Rd 21-5 Section - Kneehills Creek



- greenish grey pedogenic slts, very uniform, massive
- pale grey fine-grained ss, well sorted, sharp base and top, low-angle lamination
- greenish grey pedogenic slts, few thin very fine-grained ss and sideritic beds
- pale grey silty very fine-grained ss, f-up, rxl, slts beds at top
- greenish grey pedogenic slts
- brown carbonaceous shale
- pale grey fine-grained ss, sharp base and top, rxl
- greenish grey silty shale, pedogenic, very uniform, few silty/sandy horizons
- brown carbonaceous shale
- pale grey fine-grained ss
- brown carbonaceous shale
- pale grey very fine-grained ss
- brown carbonaceous shale
- greenish grey silty shale, pedogenic, very uniform
- pale grey very fine- to fine-grained ss, well sorted, f-up, sharp base with scours, txb
- greenish grey pedogenic silty shale, very uniform, massive, several thin horizons of sideritic concretions near base
- pale grey fine-grained ss, f-up to interbedded very fine-grained ss/slts, low-angle lamination with rxl at top
- greenish grey pedogenic slts
- pale grey fine-medium-grained ss, well sorted, uniform, slightly f-up, low-angle with rxl at top
- greenish grey pedogenic slts
- pale grey fine-grained ss, multistoried, 3 stories separated by silty zones, low-angle, capped by thin but prominent sideritic bed
- greenish grey pedogenic slts
- grey to buff fine-grained ss, sharp base and top, rxl
- greenish grey pedogenic sandy slts, massive, uniform, few thin very fine-grained ss beds
- pale grey to buff fine-grained ss, f-up, silty beds at top, low-angle lamination
- greenish grey sandy pedogenic slts, few thin very fine- to fine-grained ss and horizons small sideritic concretion
- pale grey to buff fine- to medium-grained ss, f-up, lag of grit and sideritic nodules, low-angle lamination
- greenish grey pedogenic slts, few thin very fine-grained ss beds and sideritic horizons
- black coal, sharp base and top, extensive
- grey silty shale, f-up to gradational top with more carbinaceous material
- greenish grey pedogenic slts, in 2 f-up stories, capped by sideritic concretion beds, several brown carbonaceous shale beds
- pale grey fine-grained ss, scour based lens 30 m wide, rxl
- greenish grey pedogenic slts, numerous thin very fine-grained ss beds, few horizons of large sideritic concretions
  few more carbonaceous beds
- greenish grey pedogenic very fine-grained ss to slts, f-up, sharp base
- greenish grey pedogenic slts, sandy at base, f-up, more carbonaceous at top, several rusty horizons, generally poorly exposed
- black coal, sharp top
- brown carbonaceous shale, gradational top
- grey to greenish grey pedogenic shaly slts, f-up, sharp base, gradational top, horizon of large sideritic concretions near base
  few brownish carbonaceous streaks
- greenish grey very sandy slts, f-up, many thin pale grey to rusty very fine- to-fine-grained ss beds, capped by thin sideritic horizon
- black coal, shaly splits, lignitic
- brown carbonaceous shale
- grey shaly slts, slightly f-up to gradational top
- brown carbonaceous shale, sharp top, abundant wood/leaf litter
- black coal

Hesketh Section - Kneehills Creek



- greenish grey pedogenic slts, massive, uniform, blocky
- black lignitic coal
- grey mudstone

- pale grey fine- to medium-grained ss, scoured base, lens-shaped over 10's metres, few greenish grey interbeds, slightly f-up, low-angle and txb

- interbedded greenish grey pedogenic slts, grey mudstone and pale grey very fine-grained ss up to 1.5 m thick, several thin horizons sideritic concretions

- black coal
- thinly interbedded grey mudstone and pale grey very fine-grained ss

- black coal

- thinly interbedded grey mudstone, greenish grey slts and very fine-grained ss

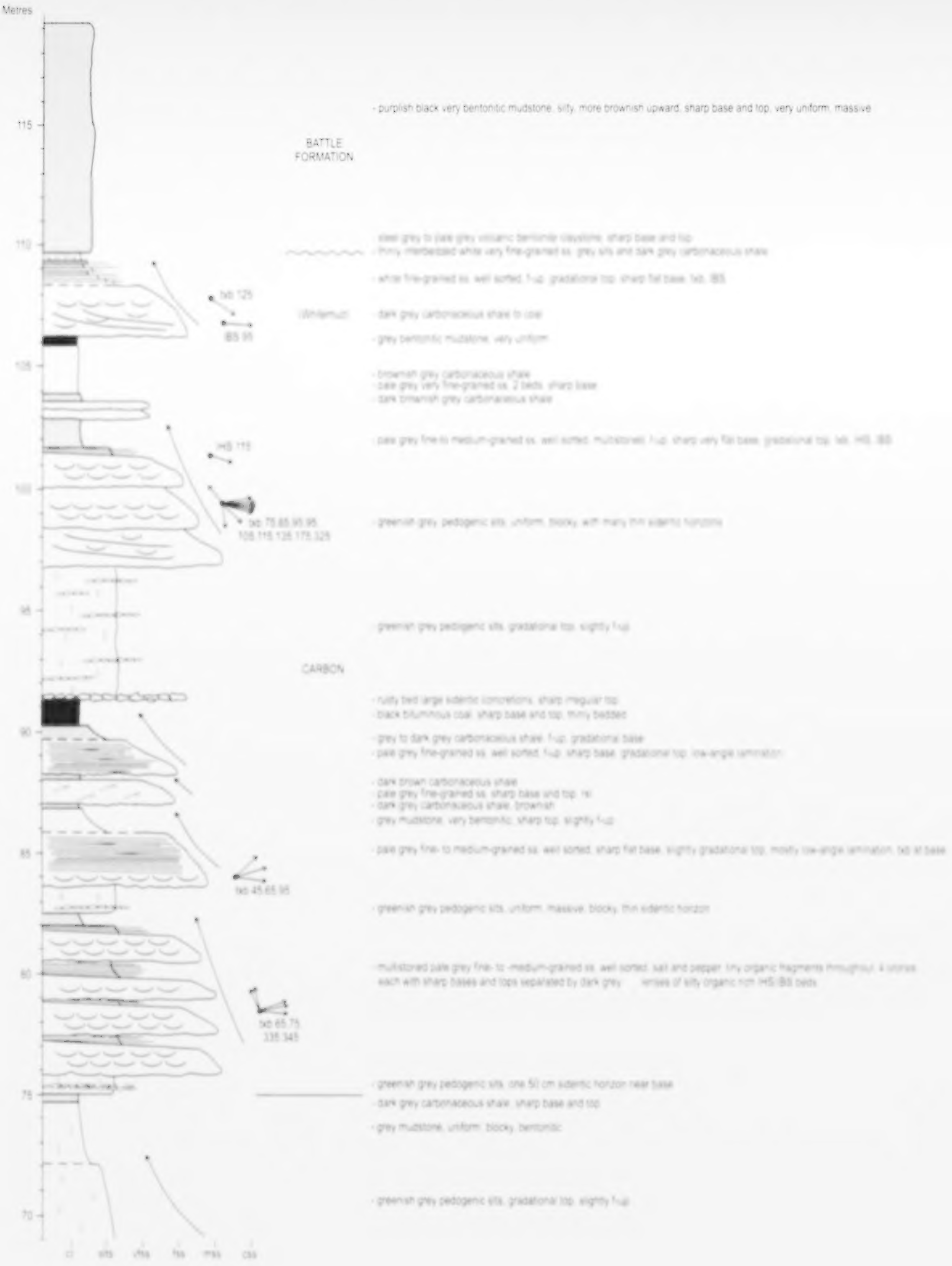
- thin black lignitic coal

- interbedded greenish grey pedogenic slts and pale grey very fine-grained ss, several thin horizons sideritic concretions

- black coal

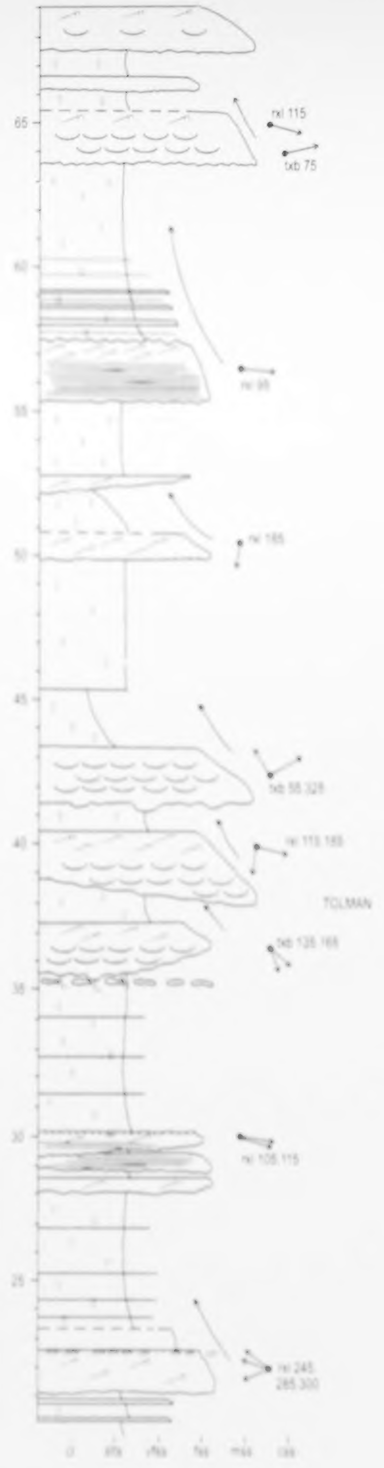
- pale grey fine- to medium-grained ss, well sorted, thick bedded, txb, slightly f-up, likely sharp base and top

Horseshoe Canyon Section, Kneehills Creek



Metres
115
110
105
100
95
90
85
80
75
70
cl
slts
vfss
fss
mss
css
BATTLE FORMATION
Whitemud
CARBON
txb 125
IBS 95
HS 115
txb 75 85 95 95
105 115 135 175 325
txb 45 65 95
txb 65 75
335 345
- purplish black very bentonitic mudstone, silty, more brownish upward, sharp base and top, very uniform, massive
- steel grey to pale grey volcanic bentonite claystone, sharp base and top
- thinly interbedded white very fine-grained ss, grey slts and dark grey carbonaceous shale
- white fine-grained ss, well sorted, f-up, gradational top, sharp flat base, txb, IBS
- dark grey carbonaceous shale to coal
- grey bentonitic mudstone, very uniform
- brownish grey carbonaceous shale
- pale grey very fine-grained ss, 2 beds, sharp base
- dark brownish grey carbonaceous shale
- pale grey fine-to medium-grained ss, well sorted, multistoried, f-up, sharp very flat base, gradational top, txb, HS, IBS
- greenish grey pedogenic slts, uniform, blocky, with many thin sideritic horizons
- greenish grey pedogenic slts, gradational top, slightly f-up
- rusty bed large sideritic concretions, sharp irregular top
- black bituminous coal, sharp base and top, thinly bedded
- grey to dark grey carbonaceous shale, f-up, gradational base
- pale grey fine-grained ss, well sorted, f-up, sharp base, gradational top, low-angle lamination
- dark brown carbonaceous shale
- pale grey fine-grained ss, sharp base and top, rei
- dark grey carbonaceous shale, brownish
- grey mudstone, very bentonitic, sharp top, slightly f-up
- pale grey fine- to medium-grained ss, well sorted, sharp flat base, slightly gradational top, mostly low-angle lamination, txb at base
- greenish grey pedogenic slts, uniform, massive, blocky, thin sideritic horizon
- multistoried pale grey fine- to -medium-grained ss, well sorted, salt and pepper, tiny organic fragments throughout, 4 stories
each with sharp bases and tops separated by dark grey lenses of silty organic rich IHS/IBS beds
- greenish grey pedogenic slts, one 50 cm sideritic horizon near base
- dark grey carbonaceous shale, sharp base and top
- grey mudstone, uniform, blocky, bentonitic
- greenish grey pedogenic slts, gradational top, slightly f-up

Horseshoe Canyon Section, Kneehills Creek cont.



- pale grey fine- to medium-grained ss. well sorted, sharp base, gradational top, txb, rxl

- greenish grey pedogenic slts
- pale grey fine-grained ss
- greenish grey pedogenic slts, uniform, blocky

- pale grey fine- to medium-grained ss, well sorted, sharp base, gradational top, txb, rxl, f-up

- greenish grey pedogenic slts, f-up, few pale grey very fine-grained ss beds up to 30 cm near base

- pale grey fine-grained ss, sharp base with sideritic lag, sharp rippled top, low-angle lamination

- greenish grey pedogenic slts, uniform, blocky

- pale grey fine-grained ss, lens-shaped, poorly exposed, rxl

- greenish grey pedogenic slts, f-up

- pale grey fine-grained ss, well sorted, f-up, sharp flat base, gradational top, rxl

- greenish grey pedogenic slts, uniform, massive, blocky

- grey mudstone, slightly f-up, sharp top, uniform, massive, blocky

- pale grey fine- to medium-grained ss, well sorted, slightly f-up, sharp base with small scours and lag of dinosaur bone fragments, more gradational top, txb
- greenish grey sandy slts, pedogenic

- pale grey fine-to medium-grained ss, well sorted, deeply scoured base, txb, rxl

- greenish grey sandy slts, pedogenic

- pale grey fine-grained ss, well sorted, sharp scoured base, wide shallow lens-shape, txb, rxl

- greenish grey pedogenic slts, uniform, massive, few thin very fine-grained ss beds, capped by 30 cm horizon of large isolated sideritic concretions with wood fragments and roots

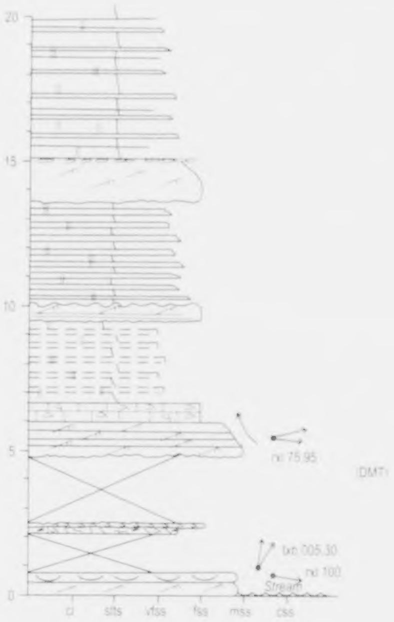
- multistoried set of 3 pale grey fine-grained ss lenses which pinch out laterally over 30 m, each with sharp base and gradational top and low-angle lamination and rxl, thin sideritic concretion bed at top

- greenish grey pedogenic slts, uniform, massive, few thin very fine-grained ss beds

- buff coloured very fine-grained ss, well sorted, sharp base, gradational top

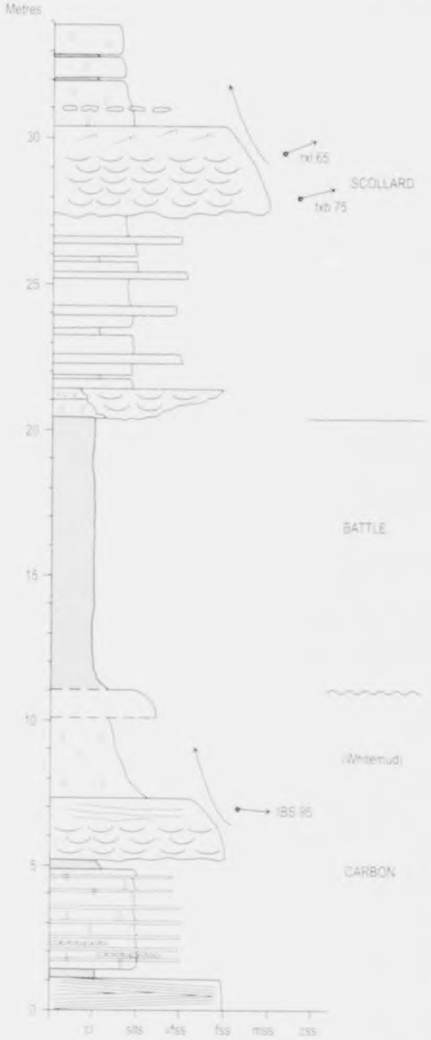
- pale grey fine-grained ss, well sorted, sharp base and top, capped by sideritic horizon, rxl

Horseshoe Canyon Section, Kneehills Creek cont.



- thinly interbedded greenish grey pedogenic slts and pale grey very fine-grained ss
- pale grey fine-grained ss, poorly exposed, capped by sideritic concretions, rxl
- thinly interbedded greenish grey pedogenic slts and pale grey very fine-grained ss
- grey fine-grained ss, well sorted, sharp flat base, sharp rippled top, low-angle lamination
- thinly interbedded greenish grey pedogenic slts and very fine-grained ss in 10-20 cm beds, with gradational boundaries
- dark greenish grey sandy limestone with abundant *in situ* oyster shells
- grey medium-grained ss, well sorted, thin bedded, very uniform, sharp top and base, rxl
- greenish grey very fine-grained ss, well sorted, abundant burrows/disarticulated pelecypod shells/wood fragments, vertical *Skolithos* and subhorizontal *Planolites* burrows, upper 5 cm is *in situ* oyster shells in sharp based coarser bed, sharp base and top, very calcareous
- pale grey fine-to medium-grained ss in 2 thin beds, well sorted, sharp bases and tops, lower rxl, upper txb

Horseshoe Canyon West Section - Kneehills Creek



- yellow grey shaly slts to silty shale, very uniform, pedogenic, horizon of large sideritic concretions near base, few grey bentonitic mudstones with carbonaceous matter

- yellow buff to rusty fine- to medium-grained ss, well sorted, sharp scoured base, txb, rxl

- thinly interbedded yellowy grey muddy slts and pale grey mudstone and grey very fine-grained ss, beds up to 50 cm ss:slts = 1:3, sharp base may downcut

- greenish grey pedogenic shaly slts, replaced to S by scour-based pale grey to white fine-grained ss with txb and 50 cm steel grey hard vesicular bentonite tuff bed which breaks into irregular conchoidal pieces, ss lens extends over about 50 m, may relate to overlying sediments

- dark brownish purplish black mudstone, very uniform, very bentonitic, gradational base, fairly sharp top

- brownish grey slightly carbonaceous shale
- pale grey very fine-grained silty ss, gradational base and top

- greenish grey, pedogenic slts, f-up, more greyish upward, gradational top

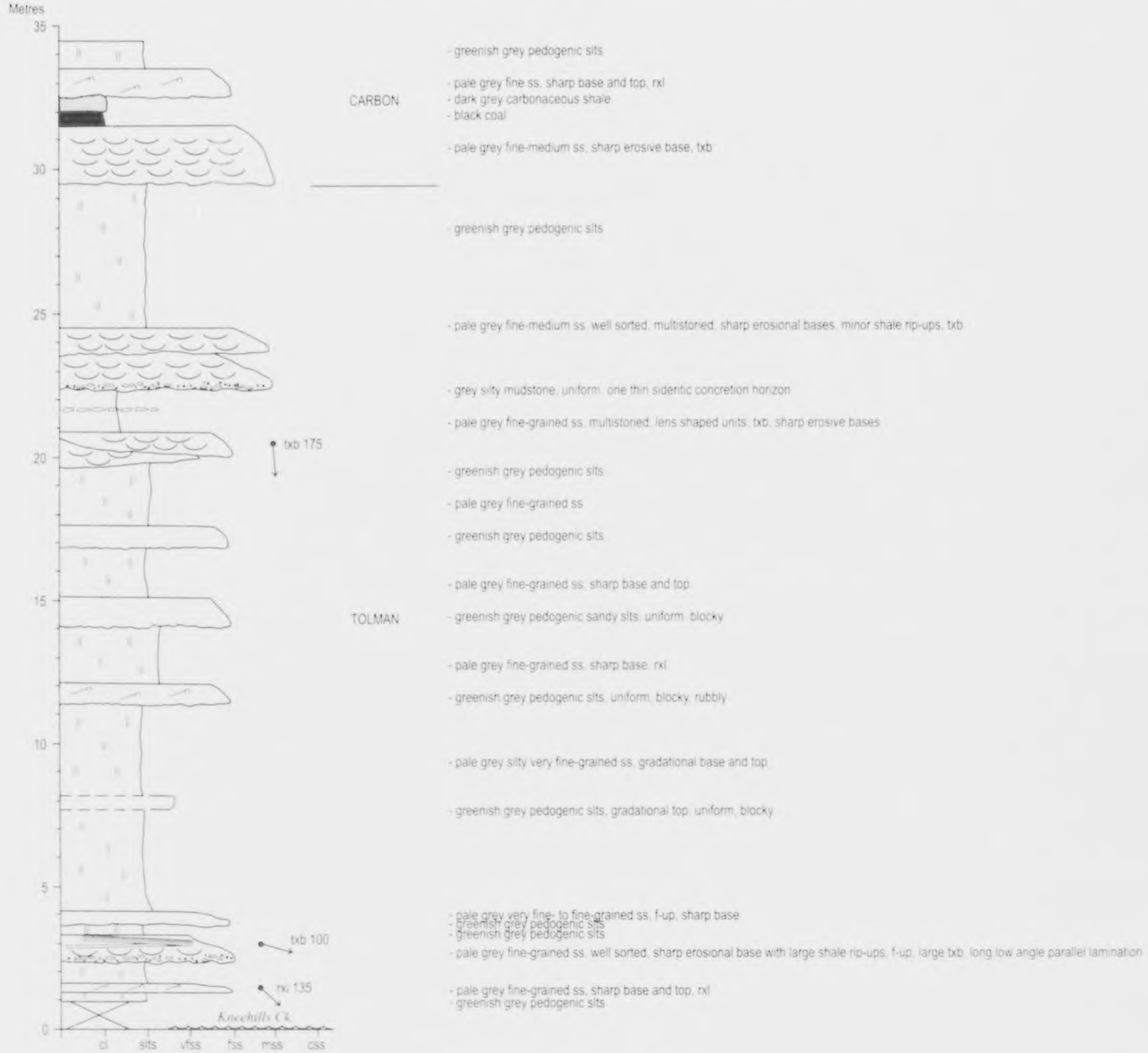
- pale grey to white fine-grained ss, well sorted, sharp base, gradational, top, IBS and txb

- brown carbonaceous shale, gradational base, sharp top

- greenish grey pedogenic slts interbedded with silty very fine-grained ss, ss:slts = 1:5, slightly f-up, few thin sideritic horizons near base

- brownish grey carbonaceous shale, coaly in middle
- pale grey fine-grained ss, well sorted, sharp base and top, low-angle lamination

Carbon Gas Plant Composite Section - Kneehills Creek


Metres
35
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cl
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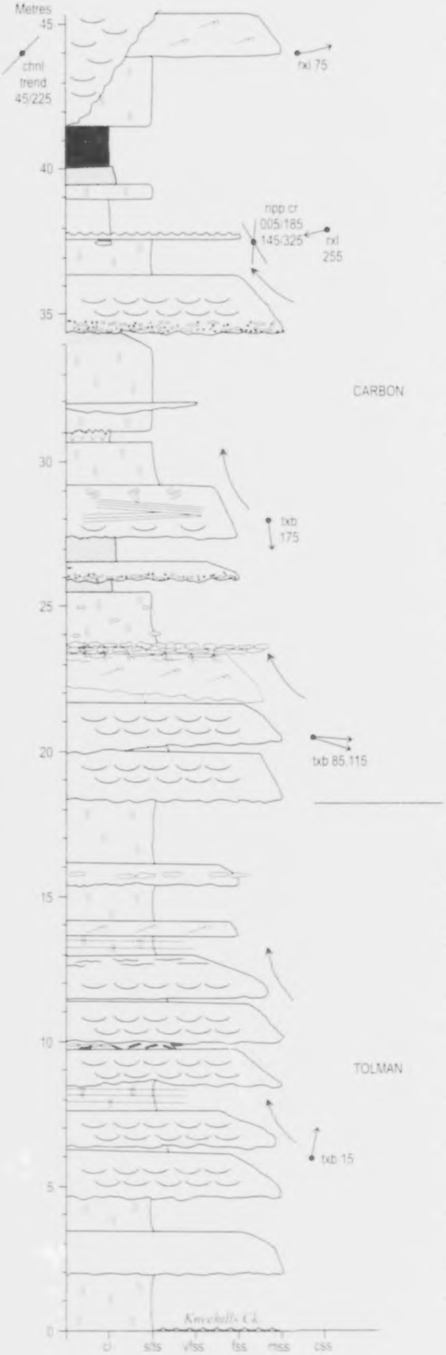
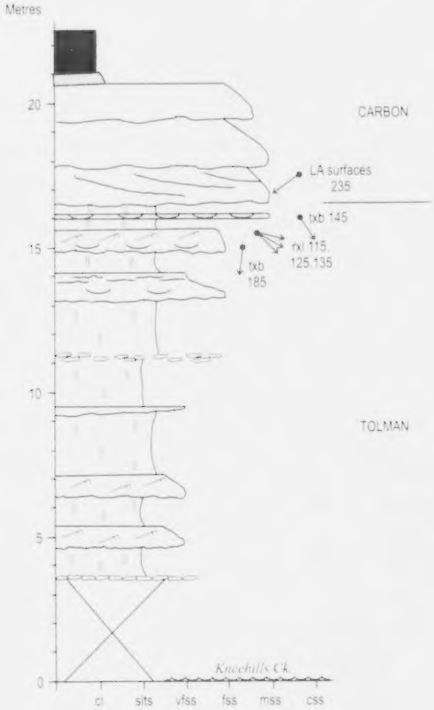
vfss
fss
mss
css
CARBON
TOLMAN
txb 175
txb 100
rxl 135
Kneehills Ck.
- greenish grey pedogenic slts
- pale grey fine ss, sharp base and top, rxl
- dark grey carbonaceous shale
- black coal
- pale grey fine-medium ss, sharp erosive base, txb
- greenish grey pedogenic slts
- pale grey fine-medium ss, well sorted, multistoried, sharp erosional bases, minor shale rip-ups, txb
- grey silty mudstone, uniform, one thin sideritic concretion horizon
- pale grey fine-grained ss, multistoried, lens shaped units, txb, sharp erosive bases
- greenish grey pedogenic slts
- pale grey fine-grained ss
- greenish grey pedogenic slts
- pale grey fine-grained ss, sharp base and top
- greenish grey pedogenic sandy slts, uniform, blocky
- pale grey fine-grained ss, sharp base, rxl
- greenish grey pedogenic slts, uniform, blocky, rubbly
- pale grey silty very fine-grained ss, gradational base and top
- greenish grey pedogenic slts, gradational top, uniform, blocky
- pale grey very fine- to fine-grained ss, f-up, sharp base
- greenish grey pedogenic slts
- greenish grey pedogenic slts
- pale grey fine-grained ss, well sorted, sharp erosional base with large shale rip-ups, f-up, large txb, long low angle parallel lamination
- pale grey fine-grained ss, sharp base and top, rxl
- greenish grey pedogenic slts

Appleyard Coulee - Kneehills Creek



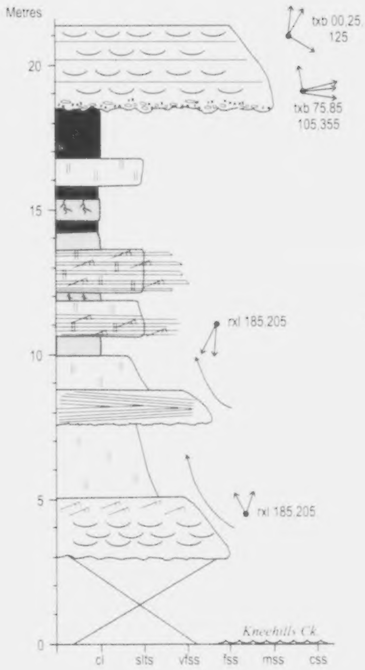
- pale grey fine- to medium-grained ss, sharp flat base, rxl
- greenish grey pedogenic sandy slts
- black bituminous coal
- dark grey carbonaceous shale, sharp base, gradational top, becomes more brown and coaly toward top
- greenish grey pedogenic slts
- grey mudstone, very uniform
- thin continuous bed brown fine-grained ss, well sorted, sharp base and top, straight-crested ripples
- greenish grey pedogenic slts, single large isolated sideritic concretion at top
- pale grey to brownish grey fine- to medium-grained ss, well sorted, slightly f-up, erosional base with coaly rip-ups and sideritic concretions, txb
- greenish grey pedogenic slts, f-up at top to more carbonaceous mudstone
- pale grey very fine-grained ss, sharp base, lens shaped, pinches out over 5 m
- greenish grey pedogenic slts
- yellowish grey clay-rich bentonite, sharp base, sharp irregular top
- greenish grey pedogenic slts
- pale grey fine-grained ss, well sorted, sharp base, txb, low-angle lamination, convolute lamination at top
- brownish grey slightly carbonaceous mudstone
- pale grey fine-grained ss, well sorted, f-up, erosional base with coaly rip-ups
- dark grey carbonaceous shale, wood fragments
- greenish grey pedogenic slts, sharp base and top, scattered small sideritic concretions
- horizon of large sideritic concretions with roots
- pale grey fine- to medium-grained ss, multistoried, well sorted, slightly f-up at top, erosional base, 3 units separated by thin lenses of slts, txb
- greenish grey pedogenic slts, uniform, blocky, rubbly
- pale grey fine-grained ss, sharp base and top, large scattered sideritic concretions
- greenish grey pedogenic slts, uniform, blocky
- pale grey fine-grained ss, well sorted, rxl
- greenish grey pedogenic slts, few thin very fine-grained ss beds
- pale grey fine- to medium-grained ss, multistoried, well sorted, f-up units separated by thin slts lenses, sideritic concretions and large wood fragments in one
- greenish grey pedogenic slts, sideritic concretions, thin very fine-grained ss beds
- pale grey to buff fine- to medium-grained ss, multistoried, well sorted, slightly f-up, thin lens of slts separates units, txb
- greenish grey pedogenic slts
- pale grey fine- to medium-grained ss, well sorted, sharp base, slightly f-up
- greenish grey pedogenic slts, uniform, blocky

Weismer's RR Cut- Kneehills Creek



- black bituminous coal, woody, sharp base and top
- dark grey carbonaceous shale
- pale grey fine- to medium-grained ss, multistoned, well sorted, f-up, sharp erosional bases, sharp tops, large low angle surfaces near base
- buff to brownish medium-grained ss, well sorted sharp base and top, txb
- greenish grey pedogenic sandy siltstone
- pale grey fine-grained ss, sharp base with lag of large ironstone concretions, sharp top, rxl, txb
- greenish grey pedogenic sandy siltstone
- pale grey fine-grained ss, well sorted, sharp base, f-up, gradational top with silty interbeds
- greenish grey pedogenic sandy siltstone, uniform, rubbly
- discontinuous horizon large ironstone concretions, sharp top, rxl, txb
- greenish grey pedogenic siltstone, uniform, blocky
- pale grey very fine- to fine-grained ss, well sorted, lens shaped, scour base, flat top
- greenish grey pedogenic sandy siltstone
- pale grey very fine-grained ss, sharp base, rxl
- greenish grey pedogenic siltstone
- pale grey very fine-grained ss, well sorted, sharp base, rx
- greenish grey pedogenic siltstone, uniform, blocky
- thin horizon of large ironstone concretions

Carbon East RR Cut - Kneehills Creek

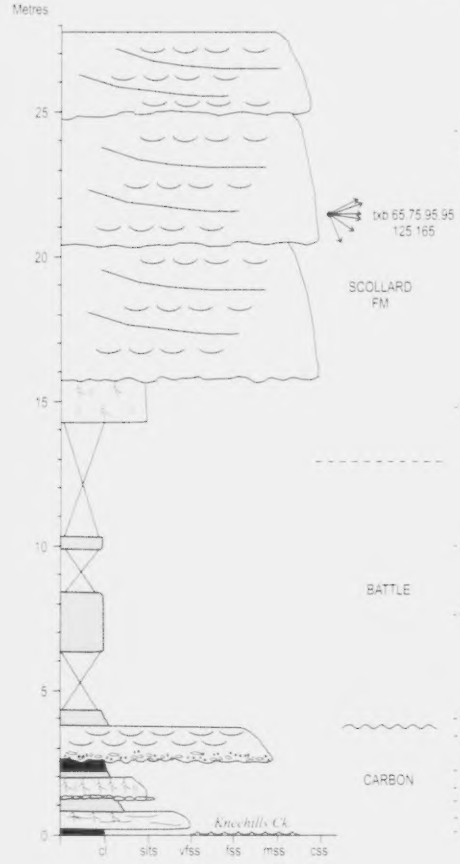


- pale grey medium-grained ss, well sorted, f-up, erosional scour base with lag of large coal rip-ups and granules, txb
- black bituminous coal, massive, charcoal-rich, blocky fracture
- greenish grey pedogenic slts, sharp base and top
- black lignitic coal
- dark grey carbonaceous mudstone, roots
- black lignitic coal, muddy
- dark grey carbonaceous mudstone, sharp base and top
- thinly interbedded greenish grey pedogenic slts and pale grey very fine-grained ss, ss:slts = 1:2, rxl
- dark grey carbonaceous, mudstone, coaly fragments, roots

CARBON

- greenish grey pedogenic slts, sharp base and top
- thinly interbedded greenish grey sandy slts and pale grey very fine-grained ss, sharp bases and rxl, few thin rusty sideritic concretion horizons
- dark grey carbonaceous mudstone
- greenish grey pedogenic slts, slightly f-up
- pale grey very fine-to fine-grained ss, sharp base, low-angle lamination
- greenish grey slts, pedogenic, uniform, massive, slightly f-up
- pale grey to buff fine-grained ss, well sorted, sharp base and top, slightly f-up, mostly txb, rxl at top

Carbon West Section - Kneehills Creek



- rusty brownish yellow medium- to coarse-grained ss. well sorted. feldspathic. thick bedded. multistoried. sharp erosional base with coaly and green silt rip-ups. very large troughy IBS. surfaces separate txb cosets 1 m thick

- greenish grey pedogenic slts. uniform. blocky. massive. vertical pedogenic structure. slickensides. roots

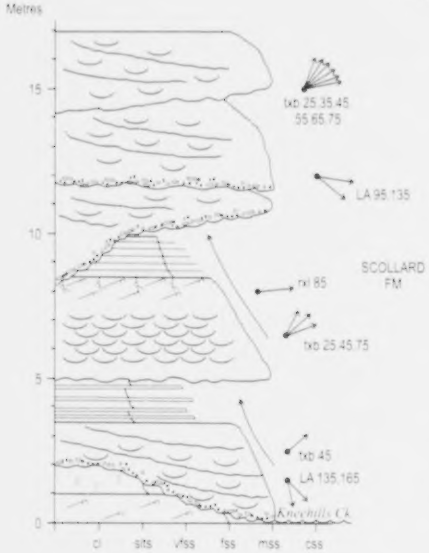
- dark purplish black mudstone. organic-rich. bentonite. very uniform and massive

- dark purplish black mudstone. organic-rich. bentonite. very uniform and massive

- dark grey carbonaceous mudstone
- pale grey to white fine-to medium-grained ss. well sorted. f-up. sharp scoured base. lag of coaly rip-ups. txb

- black carbonaceous shale to coal. more coaly upward. sharp base and top
- greenish grey pedogenic sandy slts. f-up. slickensides. blocky. fractured. abundant vertical roots
- brownish grey silty carbonaceous mudstone. poorly exposed. capped by sideritic horizon with sharp top
- pale grey very fine-grained ss. well sorted. sharp base. silty. thin carbonaceous partings. roots at top
- black lignitic coal

Highway 21 RR Cut Section - Kneehills Creek



- brownish grey multistoried medium-grained ss. salt and pepper. sharp scoured base cuts down to N over 50 m right through underlying unit, lag of shale rip-ups. sharp top. large LA surfaces. txb

- interbedded pale grey sandy sits and very thin pale grey very fine-grained ss. f-up

- brownish grey medium-grained ss. salt and pepper. well sorted. slightly f-up. sharp flat top with rxl. txb. vertical root traces near top. thick bedded

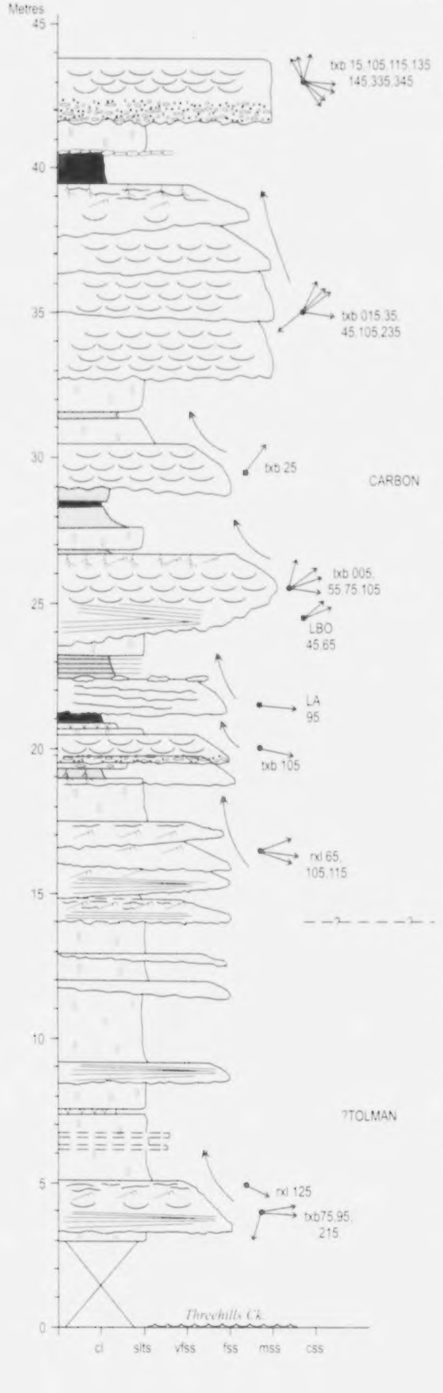
- thinly interbedded greenish grey silty mudstone with few thin very fine-grained ss beds

- brownish grey. buff weathering medium-grained ss. salt and pepper. well sorted. deeply scoured base. LA surfaces. txb. rip-ups at base

- greenish grey sandy sits. pedogenic. uniform

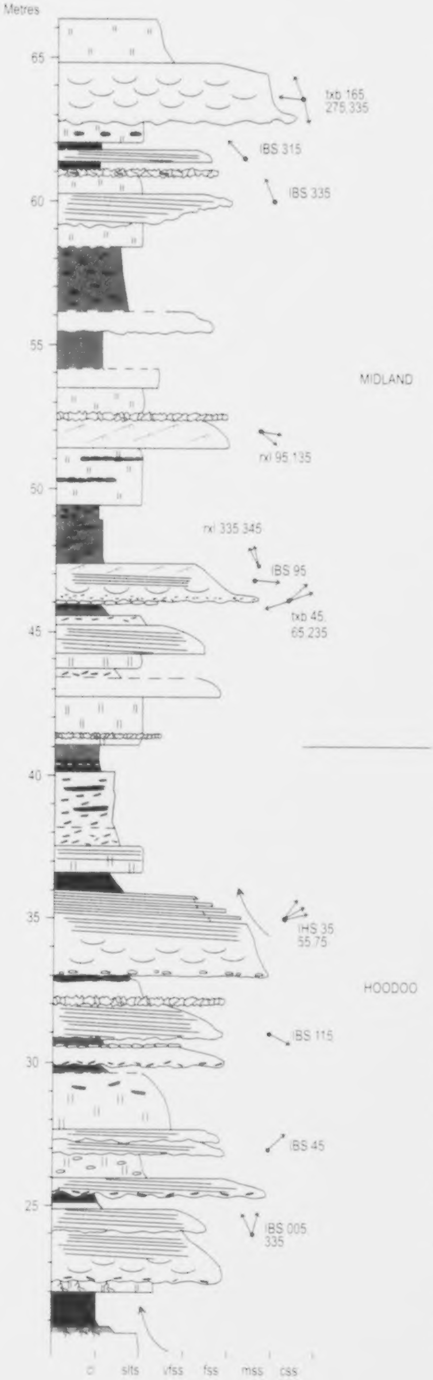
- pale grey fine-grained ss. well sorted. rxl

Three Hills Creek Section - Three Hills Creek



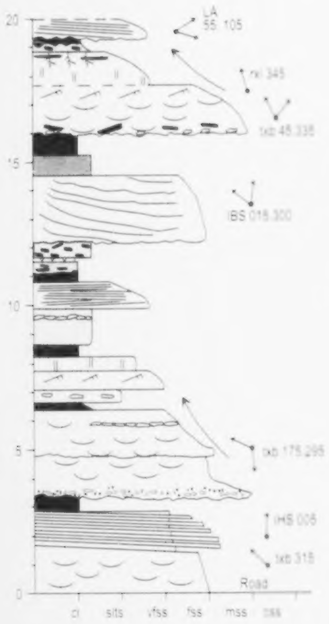
- pale grey brown weathering, medium-grained ss, well sorted, slight f-up, erosional base with large shale rip-ups and caliche nodules, txb
- greenish grey slts, pedogenic, uniform, blocky, many rusty bands
- horizon of ironstone concretions, continuous, sharp base and top
- black lignitic coal, muddy, sharp base and top
- pale grey fine- to medium-grained ss, mostly medium-grained ss, multistoried, sharp erosional base, sharp top with roots, few interbeds of slts at top, slight f-up
- greenish grey pedogenic slts, single 30 cm dark grey carbonaceous mudstone in middle
- pale grey fine-grained ss, well sorted, slight f-up, thickness to E, sharp erosive base, txb
- dark grey, carbonaceous silty mudstone
- black lignitic coal, lens shaped
- dark brownish grey carbonaceous shale, f-up, more organic rich upward, sharp top
- greenish grey pedogenic slts, sharp base and top
- brown carbonaceous shale with large coaly wood fragments
- pale grey fine- to medium-grained ss, well sorted, broadly lens shaped with pinch out to E and W over 20 cm, very erosive base, txb, LAD, rxl, long carbonized roots at top
- greenish grey pedogenic slts
- thinly interbedded greenish grey pedogenic slts and brownish carbonaceous shale
- pale grey very fine- to fine-grained ss, f-up, well sorted, sharp base, large ironstone concretions at top, LAD
- dark brownish grey carbonaceous shale
- greenish grey pedogenic slts overlain by white silty bentonite
- pale grey fine-grained ss, well sorted, slight f-up, erosional base with ironstone concretions, txb
- dark greenish grey muddy slts, small ironstone concretions
- dark brownish grey carbonaceous shale, few coaly streaks, sharp base, gradational top, vertical roots
- greenish grey pedogenic siltstone
- pale grey fine-grained ss, multistoried, well sorted, sharp erosional base, cuts out underlying slts to W, LAD, rxl, silty interbeds at top
- lens of greenish grey pedogenic slts
- pale grey fine-grained ss, f-up, sharp base, LAD, rxl, gradational top with silty interbeds
- greenish grey pedogenic siltstone
- pale grey fine-grained ss, sharp erosive base, pinches out to W over 10 m
- greenish grey pedogenic siltstone
- pale grey fine-grained ss, sharp erosive base, lens shape, thins to W
- greenish grey pedogenic siltstone, uniform, blocky
- pale grey fine-grained ss, well sorted, sharp erosional base, sharp top, LAD
- greenish grey pedogenic siltstone
- white silty bentonitic mudstone, sharp base and top, fractured
- greenish grey fine-grained ss, well sorted, slight f-up, sharp base, gradational top with silty interbeds
- pale grey fine-grained ss, well sorted, slight f-up, sharp base, gradational top with silty interbeds, mostly LAD lamination, some txb, rxl
- greenish grey pedogenic siltstone

Rosedale Bridge #2 Section



- greenish grey sandy slts, massive, uniform, blocky, pedogenic
- pale grey to buff fine- to medium-grained ss, well sorted, feldspathic, sharp erosional base, sharp top, txb
- coal
- greenish grey slts, uniform, rubbly, blocky, pedogenic
- pale grey fine-grained ss, f-up, lens-shape thins to E, erosive base, IBS
- greenish grey slts, massive, blocky, pedogenic, gradational base, sharp top
- grey to dark grey silty mudstone, fairly carbonaceous, gradational base and top, abundant tiny wood fragments
- pale grey to greenish grey very fine- to fine-grained ss, bentonitic, sharp base, gradational top
- dark brownish grey slightly carbonaceous shale
- pale grey sandy slts, gradational base and top
- greenish grey slts, uniform, blocky, massive, pedogenic
- siderite concretion horizon
- pale grey fine-grained ss, sharp flat base, rxl throughout
- greenish grey slts, uniform, blocky, rubbly, pedogenic, horizons of siderite concretions near top
- grey carbonaceous shale, tiny wood fragments
- black to brown carbonaceous shale, lignitic seams, large wood fragments
- pale grey fine-grained ss, well sorted, erosional base with mss lag, low-angle lamination, rxl, txb
- dark grey carbonaceous shale to coal, lignitic, capped by siderite concretion bed
- pale grey fine- to very fine-grained ss, flat base, gradational top, IBS
- greenish grey pedogenic slts
- brownish grey silty mudstone, abundant wood fragments
- pale grey fine-grained ss, well sorted, sharp flat base, gradational top
- greenish grey slts, sharp top, uniform, blocky, rubbly, pedogenic, horizon of large sideritic concretions with calcite fractures near base
- brown carbonaceous shale
- black soft lignitic coal, several thin laminated bentonite beds, large silicified tree root
- dark brown carbonaceous silty shale, streaks of coaly, laminated, abundant wood fragments
- grey silty mudstone, gradational base and top, abundant tiny carbonaceous fragments
- pale greenish grey slts, thin sandy layers at top, blocky, pedogenic
- dark greenish grey silty mudstone, soft, carbonaceous
- pale grey fine- to medium-grained ss, f-up at top, sharp flat base with lag of sideritic concretions, large sets of IHS/IBS, txb
- greenish grey slts, uniform, blocky, pedogenic, thin carbonaceous streak at top
- thick sideritic concretion bed, wood fragments
- pale grey fine-grained ss to slts, f-up, erosional base, IBS
- brownish grey carbonaceous shale, sharp top
- pale grey fine-grained ss, erosional base with coaly lag, gradational top, sideritic concretions at top
- black coal to carbonaceous shale
- greenish grey sandy slts, f-up to slts, gradational boundaries, uniform, blocky, pedogenic, large wood fragments
- pale grey fine-grained ss, multistoried, sharp base, IBS
- greenish grey slts, uniform, blocky, pedogenic, sideritic concretions
- pale grey fine- to medium-grained ss, erosional base with coaly rip-ups, slightly f-up, IBS
- black coal, discontinuous, large sideritic concretions
- pale grey fine-grained ss, erosional base with few coaly fragments, multistoried, txb, IBS
- brownish grey sandy slts, roots, pedogenic
- black coal, laminated, bituminous, sharp base and top
- brownish grey carbonaceous shale, lignitic, roots, gradational base and top
- grey slts, f-up, sandy at base, gradational base and top

Rosedale Bridge #2 Section cont.



- grey very fine-grained ss silty ss, sharp erosional base with lag of coaly fragments, f-up to slts, low-angle lamination
- dark grey carbonaceous shale grading up to coal, wood fragments and roots
- grey to greenish grey sandy slts, f-up to muddy slts, gradational base, sharp top, pedogenic, roots and carbonaceous seams at top

- pale grey fine- to medium-grained ss, well sorted, feldspathic, sharp slightly erosional base with lag of sideritic nodules, slightly f-up, txb, rxl at top, large wood fragments

- coal
- dark brownish grey silty mudstone, tiny wood fragments

- pale grey fine-grained ss, sharp base, abundant IBS

- brownish grey silty mudstone, tiny wood fragments
- white bentonite
- coal and carbonaceous shale

HOODOO - pale grey silty very fine-grained ss, sharp base, f-up, gradational top, low-angle lamination

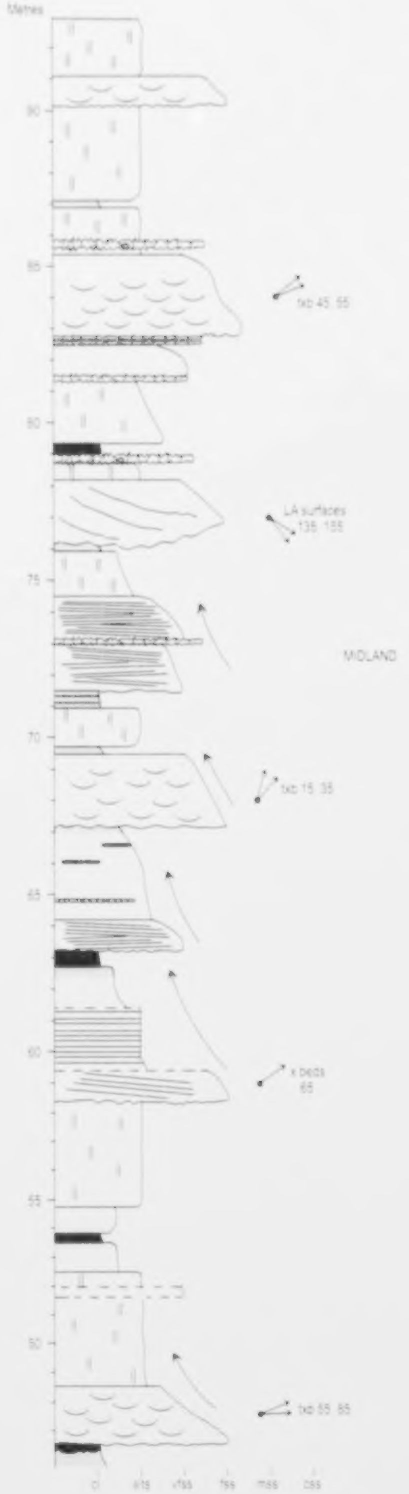
- dark brownish grey silty mudstone, poorly exposed, thin sideritic bed at top
- coal
- greenish grey sandy slts, blocky, rubbly, pedogenic
- grey very fine-grained ss, sharp base and top, rxl, carbonaceous matter on laminae
- greenish grey sandy slts, large sideritic nodules
- coal

- pale grey fine-grained ss, well sorted, sharp flat base minor erosional topography with lag of medium-grained ss and coaly fragments, multistoried, txb, f-up at top, sideritic horizon near top

- coal

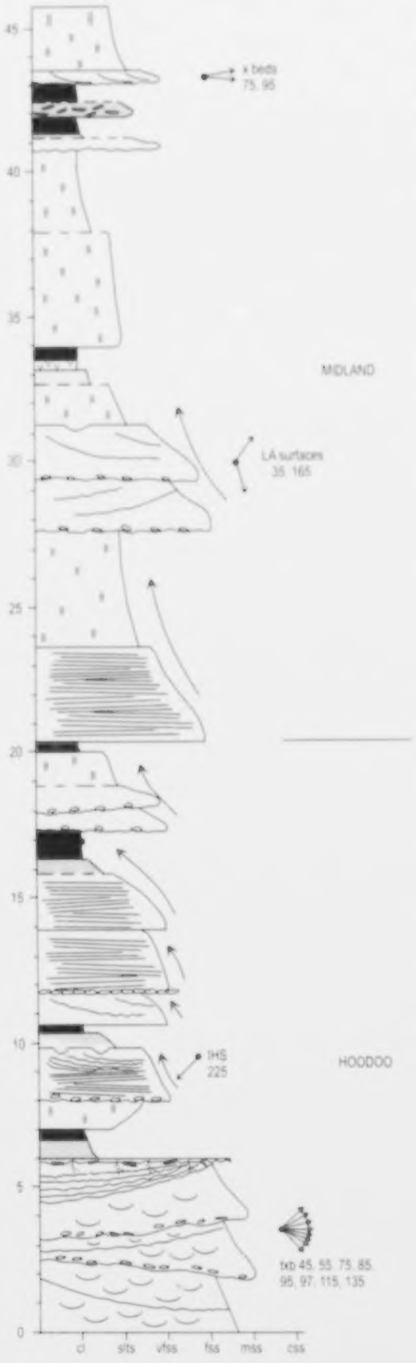
- pale grey fine-grained ss, sharp top, txb, IHS

Wayne Section



- greenish grey slts, uniform, blocky, pedogenic
- pale grey fine-grained ss, f-up, sharp base and top, txb
- greenish grey slts, blocky, uniform, pedogenic
- dark grey carbonaceous shale
- greenish grey slts, massive, blocky, pedogenic
- sideritic concretion horizon, roots
- pale grey fine-grained ss, f-up, well sorted, uniform, txb
- sideritic concretion horizon
- pale grey fine-grained ss, f-up
- sideritic concretion horizon, irregular sharp top
- greenish grey slts, massive, uniform, blocky, pedogenic, f-up
- coal, lignitic
- sideritic concretion horizon, wood fragments, roots
- grey slts, massive, blocky
- pale grey fine-grained ss, f-up, well sorted, thins to N, sharp erosional base, LA surfaces
- dark grey carbonaceous shale
- greenish grey muddy siltstone, gradational top, massive, pedogenic
- pale grey fine-grained ss, f-up, sideritic horizon at base, low angle lamination
- pale grey fine-grained ss, sharp base, low angle lamination
- dark grey carbonaceous shale, silty interbeds
- greenish grey slts, massive, blocky, pedogenic
- dark grey carbonaceous shale
- pale grey fine-grained ss, sharp base and top, txb
- greenish grey fine-grained ss, slightly f-up, more carbonaceous to top, several sideritic concretion horizons
- pale grey fine-grained ss, sharp base and top, low angle lamination
- coal, lignitic
- dark greenish grey silty mudstone, gradational base, sharp top
- thinly interbedded greenish slts and pale grey very fine-grained ss, gradational base and top
- pale grey fine-grained ss, sharp base, gradational top, low angle lamination
- greenish grey slts, massive, blocky, pedogenic
- darker greenish grey muddy slts to silty mudstone
- dark grey carbonaceous mudstone
- dark greenish grey muddy slts to silty mudstone, gradational top
- greenish grey slts, massive, blocky, pedogenic, with one sandy zone with gradational boundaries
- pale grey fine-grained ss, sharp base, gradational top, all txb
- dark grey carbonaceous shale grading up into lignitic coal

Wayne Section cont.



- greenish grey sandy sits, slightly f-up, massive, blocky, pedogenic

- pale grey very fine-grained ss, sharp base with siderite and wood fragments, gradational tops, low angle lamination
- black lignitic coal
- brownish grey sandy sits, sharp base, gradational top, abundant wood fragments
- black lignitic coal
- pale grey very fine-grained ss, f-up, sharp base, gradational top

- greenish grey silty claystone, massive, blocky, pedogenic

- greenish grey sits, massive, uniform, blocky, pedogenic, gradational top

- dark grey black carbonaceous shale to lignitic coal, large silicified wood fragments at top
- pale grey to grey very bentonitic claystone, more organic rich upward
- dark grey to rusty carbonaceous shale
- greenish grey sits, sharp base with scours, gradational top, pedogenic

- two stacked pale grey fine-grained ss units, sharp scoured bases with siderite, f-up, sharp top with sits-filled scours, 1 m wide, LA surfaces

- greenish grey sandy sits, massive, blocky, uniform, pedogenic

- dark grey carbonaceous shale, coaly streaks

- greenish grey sits, massive, blocky, pedogenic, f-up, gradational base
- pale grey fine-grained ss, well sorted, f-up, multistoried, scour bases with sideritized rip-ups, minor txb, low-angle lamination, more gradational top

- black coal, very continuous and distinct across cliff faces

- dark grey carbonaceous shale

- pale grey, very fine-grained ss, silty, f-up, well sorted, gradational top

- pale grey very fine-grained ss, f-up, well sorted, low-angle lamination

- grey to pale grey very fine-grained ss, silty, LA surfaces, capped by sideritic horizon, shalier to W

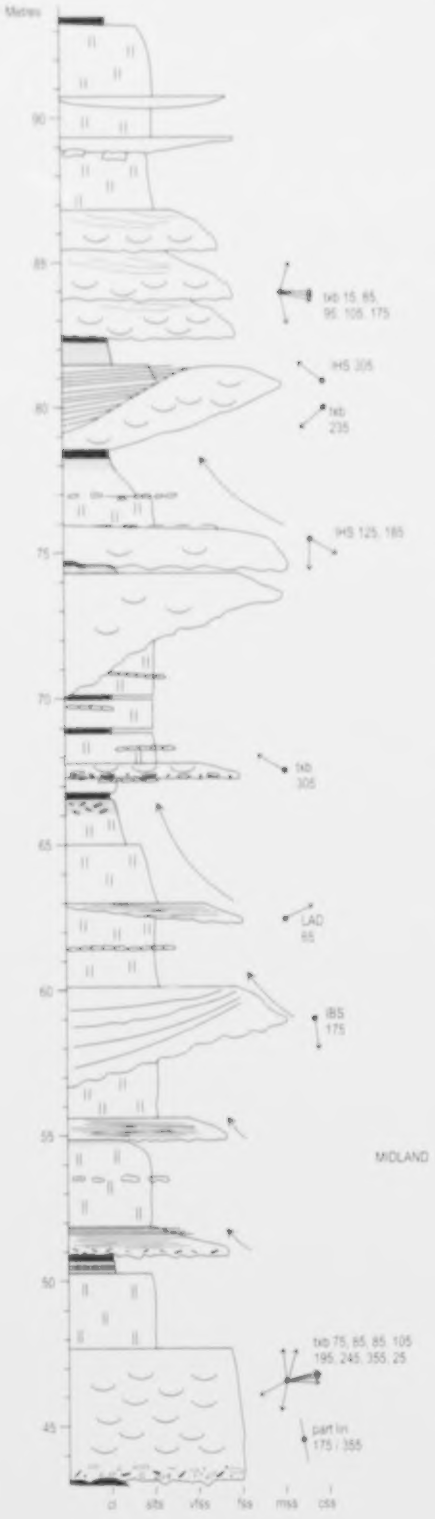
- black coal, lignitic, laterally continuous
- grey slightly sandy sits, f-up, more carbonaceous upward, sharp top

- grey to pale grey, very fine-grained ss, scoured base with rip-ups and siderite, f-up to sandy sits, sharp top with mud-filled scours, IHS

- greenish grey, muddy sits, massive, blocky, pedogenic, c-up
- dark grey carbonaceous shale grading into lignitic coal, sharp top

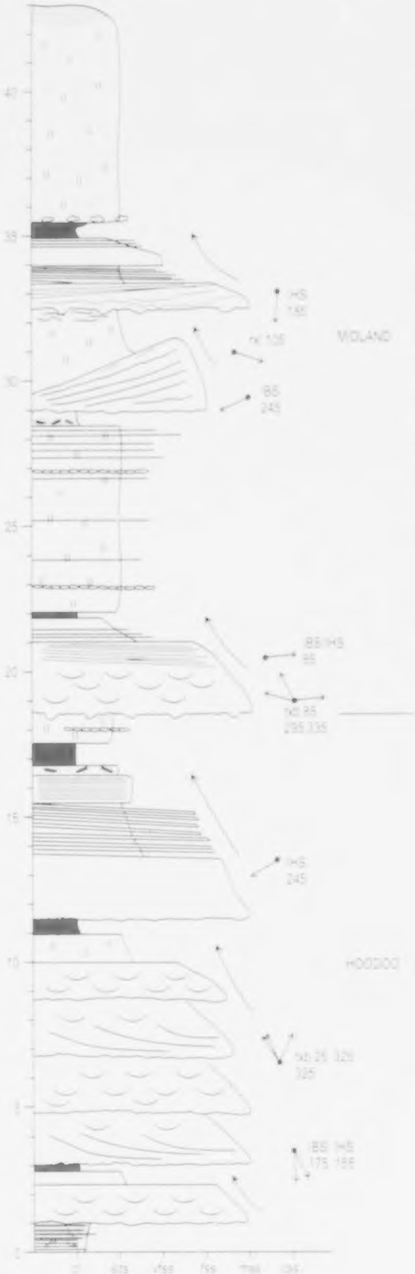
- pale grey fine- to medium-grained ss, uniform, well sorted, base not exposed, sharp flat top with siderite concretion bed and roots and wood fragments, multistoried, sideritized base with rip-ups and wood fragments, mostly large LA surfaces and txb, minor IHS near top (present at Hoodoos, 25m)

Jewel Mine Section - Rosebud River



- black coal, overlain by Quaternary
- greenish grey pedogenic sits, several thin fine-grained ss lenses
- greenish grey pedogenic sits, large sideritic concretion at top
- pale grey multistoried fine-grained ss, passes laterally into sits; 3 stories are each sharp-based and f-up, mostly txb and IBS
- black lignitic coal
- brown carbonaceous shale
- white fine- to medium-grained ss passing up into thinly interbedded IHS ss/sits, sharp flat base and top, - scour pinchout to NE and all IHS to SW, txb
- f-up sequence grey sits to grey carbonaceous silty shale to brown carbonaceous shale to lignitic coal with sharp top
- greenish grey pedogenic sits, capped by discontinuous sideritic concretion horizon
- white multistoried fine-grained ss to medium-grained ss, 2 stories separated by 30 cm dark grey carbonaceous shale to coal, deeply scoured base toward SW, more gradational top with thin IHS
- greenish grey pedogenic sits, several 30 cm brown to black carbonaceous shale to coal beds, several horizons large sideritic horizons full of petrified wood
- grey fine-grained ss, sharp base with large rounded greenish clay bentonite clasts, txb
- rusty brown mudstone, capped by horizon of sideritic concretions
- black coal
- brownish grey muddy sits, f-up to silty carbonaceous shale with wood fragments
- greenish grey, pedogenic sits, massive, rubbly
- white fine-grained ss, sharp base, pinches out to W, low-angle lamination
- greenish grey pedogenic sits, massive, uniform, distinct horizon of sideritic concretion
- pale grey fine-grained ss to medium-grained ss, deeply scoured base toward SW, full channel width = 100 m, sharp flat top marked by horizon of sideritic concretions, mostly IBS
- greenish grey pedogenic sits, massive, uniform
- pale grey fine-grained ss, sharp base, slightly f-up, low-angle lamination
- greenish grey pedogenic sits, brownish more carbonaceous sits at top, one horizon of large sideritic concretions in middle
- white fine-grained ss, f-up to thinly interbedded very fine-grained ss and sits, sharp base with small scours and coaly log
- black lignitic coal
- brown carbonaceous shale, coaly with thin brown claystone bentonite in middle
- greenish grey pedogenic sits, massive, uniform
- pale grey fine-grained ss, well sorted, sharp base with small scours with large of wood fragments, caliche nodules/concretions, txb
- black to brown lignitic coal

Jewel Mine Section - Rosebud River cont.



- greenish grey bentonitic slts: massive, uniform, pedogenic, sharp base with large concretions, upper 50 cm is brownish grey carbonaceous shale with roots

- black coal: sharp top marked by layer of petrified wood fragments
- pale grey very fine-grained ss: silty, sharp flat base, f-up to interbedded ss and slts

- thinly interbedded very fine-grained ss and slts in brownish grey IHS beds: more carbonaceous upward
- white fine- to medium-grained ss: sharp base with small scours, f-up, IBS grades into IHS toward SW

- greenish grey pedogenic slts: gradational base, sharp top, thin carbonaceous laminae toward top

- pale grey to rusty fine-grained ss: well sorted, pinches out from top toward SW, abundant thin horizons of sideritic concretions indicate IBS

- brown carbonaceous shale: muddier upward, abundant wood fragments and leaves

- greenish grey pedogenic slts: uniform, massive, rubbly, few horizons of sideritic concretions, numerous thin very fine- to fine-grained ss beds with sharp bases

- black carbonaceous shale
- greenish grey bentonitic shaly slts: massive, vague IHS at base

- pale grey fine- to medium-grained ss: sharp base with small scours, txb and l - -angle IHS lamination at top

- greenish grey muddy slts: massive, uniform, horizon of small sideritic concretions

- black coal: lignitic to subbituminous, more muddy upward, sharp top
- brown slts: massive, sharp base and top, large wood fragments
- brownish grey sandy slts: thin bedded

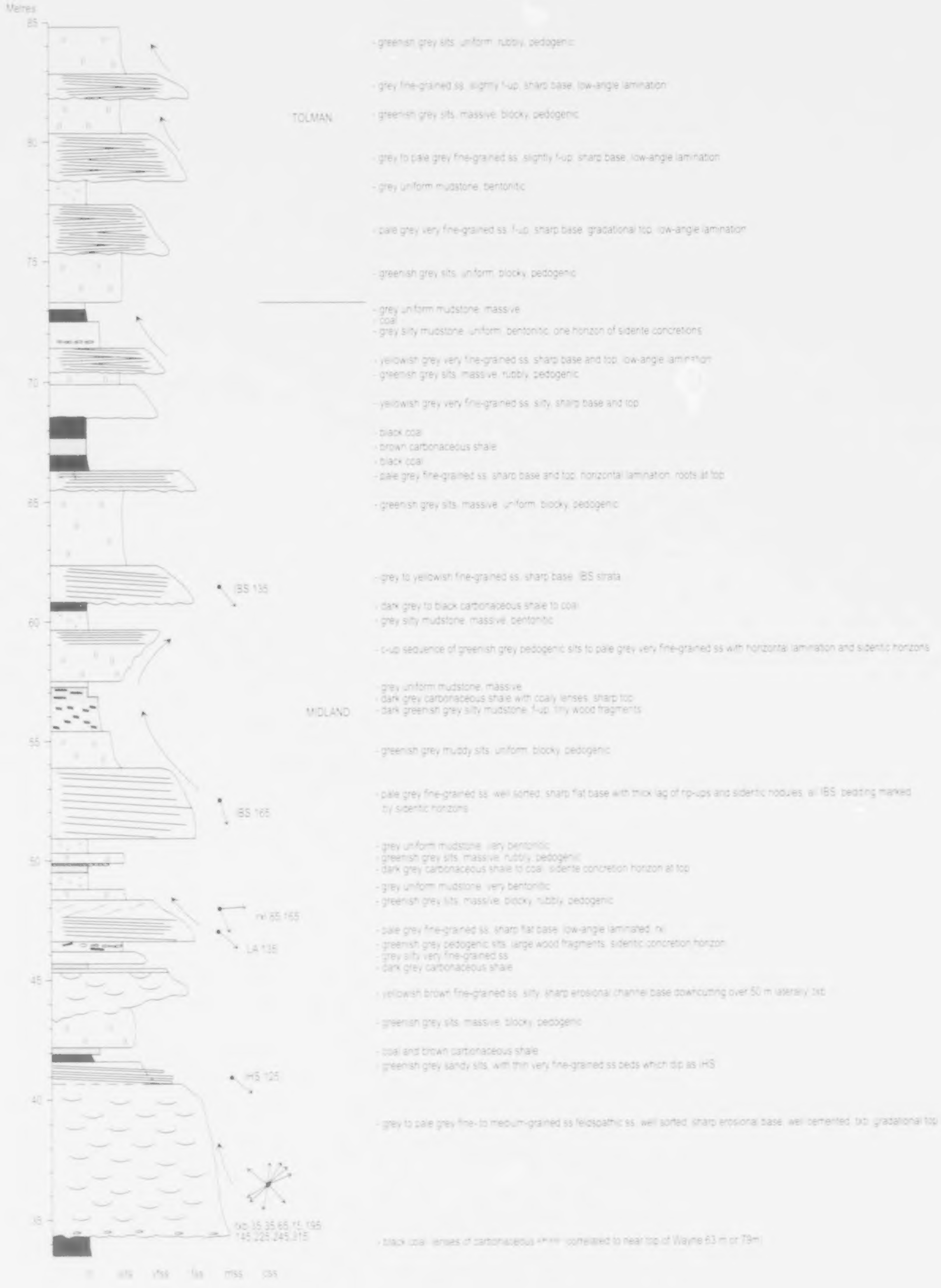
- pale grey to white fine- to medium-grained ss: well sorted, sharp base, massive in lower half, thickly interbedded shaly IHS in upper half

- black coal
- greenish grey slts: pedogenic

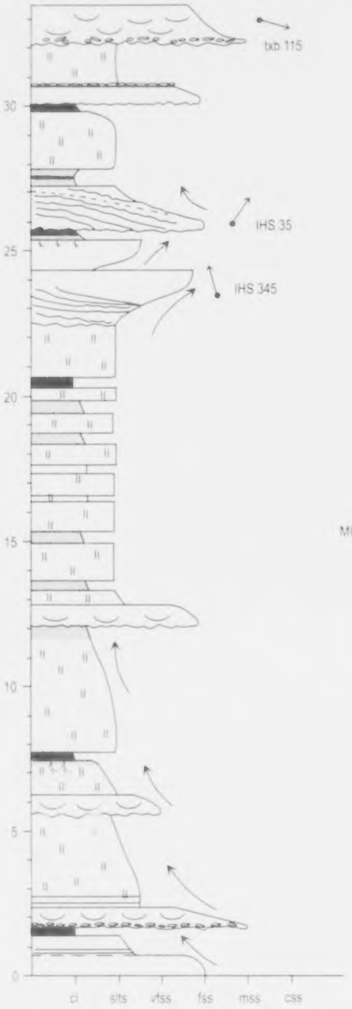
- pale grey multistoried fine- to medium-grained ss: each storey has sharp bases and f-up, mostly txb and IBS, thin coal and 50 cm slts bed above lowest storey

- brownish grey mudstone: thinly laminated, burrowing

CNR Iron Bridge Section


Metres
85
80
75
70
65
60
55
50
45
40
35
TOLMAN
MIDLAND
IBS 135
IBS 165
rxl 85 165
LA 135
IHS 125
txb 15 35 65 75 195
145 225 245 315
m
sits
vfss
fss
mss
css
- greenish grey sits, uniform, rubbly, pedogenic
- grey fine-grained ss, slightly f-up, sharp base, low-angle lamination
- greenish grey sits, massive, blocky, pedogenic
- grey to pale grey fine-grained ss, slightly f-up, sharp base, low-angle lamination
- grey uniform mudstone, bentonitic
- pale grey very fine-grained ss, f-up, sharp base, gradational top, low-angle lamination
- greenish grey sits, uniform, blocky, pedogenic
- grey uniform mudstone, massive
- coal
- grey silty mudstone, uniform, bentonitic, one horizon of siderite concretions
- yellowish grey very fine-grained ss, sharp base and top, low-angle lamination
- greenish grey sits, massive, rubbly, pedogenic
- yellowish grey very fine-grained ss, silty, sharp base and top
- black coal
- brown carbonaceous shale
- black coal
- pale grey fine-grained ss, sharp base and top, horizontal lamination, roots at top
- greenish grey sits, massive, uniform, blocky, pedogenic
- grey to yellowish fine-grained ss, sharp base, IBS strata
- dark grey to black carbonaceous shale to coal
- grey silty mudstone, massive, bentonitic
- c-up sequence of greenish grey pedogenic sits to pale grey very fine-grained ss with horizontal lamination and sideritic horizons
- grey uniform mudstone, massive
- dark grey carbonaceous shale with coaly lenses, sharp top
- dark greenish grey silty mudstone, f-up, tiny wood fragments
- greenish grey muddy sits, uniform, blocky, pedogenic
- pale grey fine-grained ss, well sorted, sharp flat base with thick lag of rip-ups and sideritic nodules, all IBS, bedding marked by sideritic horizons
- grey uniform mudstone, very bentonitic
- greenish grey sits, massive, rubbly, pedogenic
- dark grey carbonaceous shale to coal, siderite concretion horizon at top
- grey uniform mudstone, very bentonitic
- greenish grey sits, massive, blocky, rubbly, pedogenic
- pale grey fine-grained ss, sharp flat base, low-angle laminated, rxl
- greenish grey pedogenic sits, large wood fragments, sideritic concretion horizon
- grey silty very fine-grained ss
- dark grey carbonaceous shale
- yellowish brown fine-grained ss, silty, sharp erosional channel base downcutting over 50 m laterally, txb
- greenish grey sits, massive, blocky, pedogenic
- coal and brown carbonaceous shale
- greenish grey sandy sits, with thin very fine-grained ss beds which dip as IHS
- grey to pale grey fine- to medium-grained ss feldspathic ss, well sorted, sharp erosional base, well cemented, txb, gradational top
- black coal, lenses of carbonaceous shale (correlated to near top of Wayne 63 m or 79m)

CNR Iron Bridge Section cont.



- pale grey fine-grained ss, sharp erosional base, sideritic lag, with medium-grained ss grains and wood fragments

- greenish grey slts, uniform, blocky, pedogenic
- grey to buff fine-grained ss, sharp erosional base, sideritic horizon at top
- coal, carbonaceous shale streaks

- greenish grey slts, f-up at top, massive, blocky, rubbly, pedogenic

- brown carbonaceous shale, most coaly in middle

- grey fine-grained ss with IHS passing upward and northward into sandy slts, sharp base
- brown carbonaceous shale to coal, abundant wood fragments
- c-up seq of greenish grey sandy slts to pale grey silty very fine-grained ss, sharp top with roots

- distinctive yellowish brown slts with sandy IHS grading up into pale grey fine-grained ss, sharp erosional base

- greenish grey pedogenic slts

-coal

- brown to dark grey carbonaceous shale
- greenish grey pedogenic slts
- brownish grey, more carbonaceous shale

- greenish grey slts, uniform, blocky, rubbly, few finer horizons

MIDLAND

- brown carbonaceous shale
- greenish grey slts, uniform, rubbly, blocky, pedogenic

- brownish grey carbonaceous shale
- greenish grey shaly slts, massive, blocky, pedogenic
- pale grey fine-grained ss, well sorted, erosional base, sharp top, txb

- greenish grey slts, uniform, rubbly, blocky, pedogenic, slightly f-up, and more carbonaceous toward top

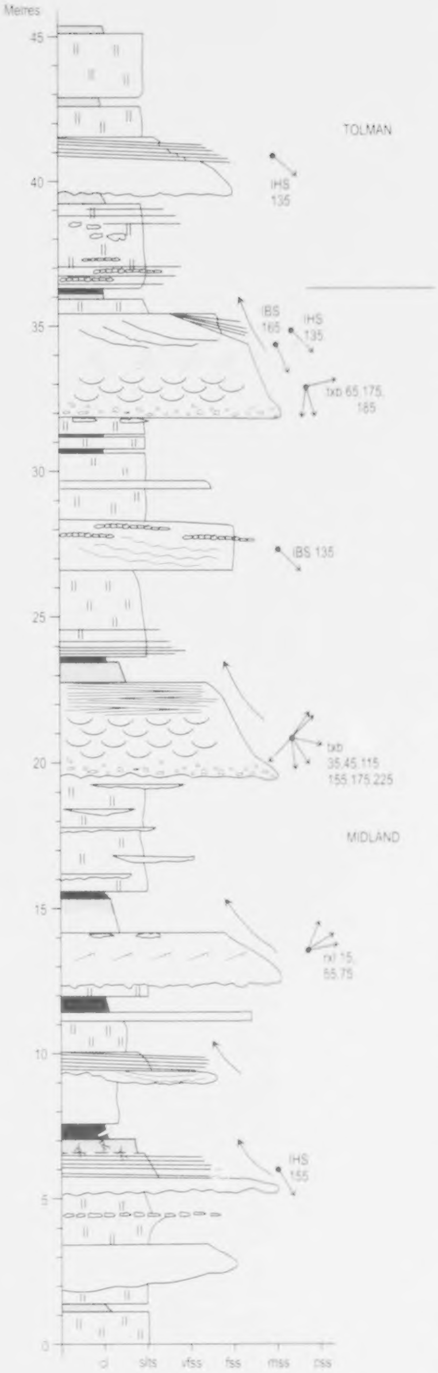
- greenish grey slts, f-up, more carbonaceous upward, uniform, blocky, pedogenic, roots

- pale grey very fine-grained ss, erosional base with 20 cm topography, txb

- greenish grey slts, sandy at base, f-up, blocky, massive, pedogenic

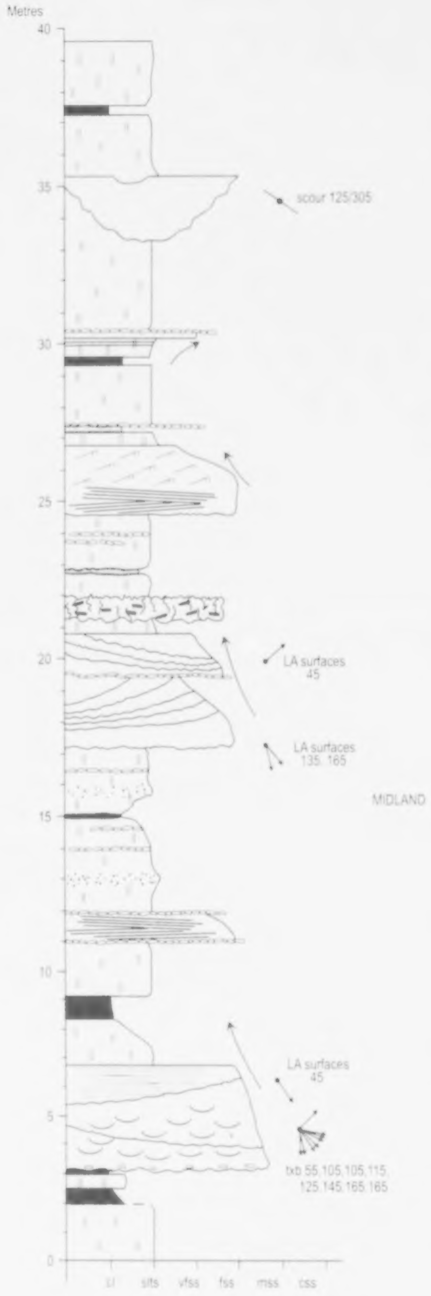
- pale grey very fine- to medium-grained ss, erosional base with sideritic lag and wood/bone fragments, f-up, well sorted, txb, sharp top
- black coal
- grey sandy slts, slightly f-up, gradational base, sharp top, very fine-grained ss beds near base
- pale grey to white fine-grained ss, well sorted, gradational top, low-angle lamination

Mile 64.5 Section - Rosebud River



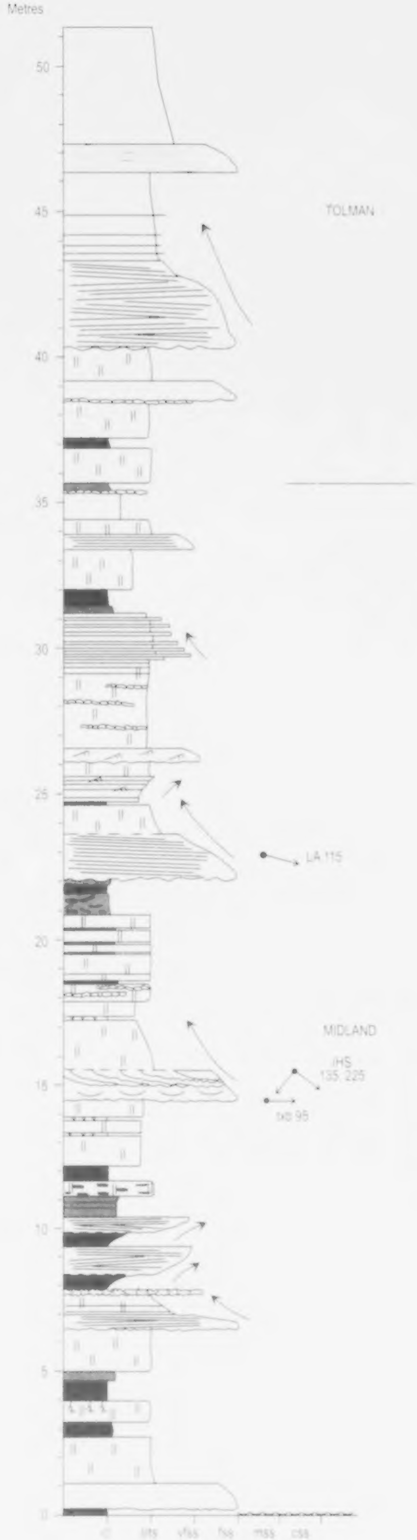
- dark grey carbonaceous shale, rusty mudstone base
- green grey pedogenic slts
- carbonaceous shale, rusty mudstone base
- greenish grey pedogenic slts
- white fine-grained ss, sharp base, f-up, IHS at top
- dark grey carbonaceous shale, rusty mudstone base
- greenish grey pedogenic slts, numerous thin rusty sideritic concretion horizons at base and also thin very fine-grained ss beds, few thin very fine ss near top, more sandy to E, more carbonaceous to W
- black carbonaceous shale to coal
- greenish grey pedogenic slts
- pale grey to white fine- to medium-grained ss, slightly f-up, sharp flat base with lag of pebbles/caliche nodules, generally txb, contorted lamination in middle, pinches out to W, IBS
- greenish grey pedogenic slts, one 20 cm fine-grained ss in middle, two 10 cm brown carbonaceous shale beds with gradational boundaries near top, capped by large sideritic concretions
- pale grey to white fine-grained ss, well sorted, no f-up, thin horizons sideritic concretions near top, IBS, sharp top
- greenish grey pedogenic slts, very uniform, many rusty hard bands near base
- black coal
- grey to dark grey silty shale
- pale grey to white very fine- to medium-grained ss, scoured base with large caliche nodules, then txb, then f-up to very fine- to fine-grained ss with horizontal to low-angle lamination, sharp top
- greenish grey pedogenic slts, few thin 20-30 cm very fine-grained ss lenses
- black coal lignitic, sharp base and top
- grey to dark grey carbonaceous shale to shale, more carbonaceous upward
- pale grey to rusty fine- to medium-grained ss, well sorted, sideritic cement, f-up to gradational top with silty beds, scoured base, rxl in middle, large sideritic concretion at top up to 1 m
- greenish grey pedogenic slts, massive, uniform
- black coal, blocky, laterally extensive
- white fine- to medium-grained ss, well sorted, sharp base and top
- greenish grey pedogenic slts, shaly, bentonitic, massive, uniform
- thinly interbedded very fine-grained ss and slts passes laterally into white fine-grained ss with IBS/IHS
- greenish grey very bentonitic silty mudstone, very uniform, massive
- black coal, large pieces petrified logs
- brown organic-rich slts, roots gradational base, sharp top
- pale grey to white very fine- to medium-grained ss, f-up, sharp scoured base, well sorted, upper part is thinly interbedded IHS very fine-grained ss and slts, gradational top
- greenish grey slts, in middle is 30 cm sandy zone with flat base and irregular top capped by large sideritic horizon and abundant wood fragments
- pale grey fine-grained ss, sharp base and top, pinches out over 20 m laterally
- greenish grey pedogenic slts
- dark grey carbonaceous shale with coaly streaks, gradational base
- greenish grey pedogenic slts, massive, blocky, uniform

Taylor Siding Section



- greenish grey pedogenic slts, massive, blocky
- black coal
- greenish grey slts, massive, blocky, pedogenic
- white fine-grained ss, lens-shaped body with deeply erosional base, pinchout over 20 m laterally, minor slts-filled scour on top
- greenish grey slts, massive, blocky, pedogenic
- c-up sequence pedogenic slts to slts and very fine-grained ss to very fine-grained ss to concretion horizon
- dark grey carbonaceous shale, sharp base and top
- greenish grey slts, massive, uniform, pedogenic
- dark grey carbonaceous shale, thin sideritic concretion zone
- greenish grey slts, massive, blocky, pedogenic
- pale grey fine-grained ss, sharp flat base, f-up in upper half, low-angle lamination near base, rxl near top
- greenish grey slts, massive, blocky, thin carbonaceous mudstone near base, discontinuous sideritic concretion horizon near top
- rusty yellow sideritic concretionary bed, erosional base, irregular top, fractures, calcite veins, silicified wood fragments
- greenish grey massive blocky slts, pedogenic, sharp top
- pale grey fine- to very fine-grained ss, f-up, multistoried, sharp base and top, low-angle lamination
- greenish grey slts, massive, blocky, uniform, pedogenic, with one thin carbonaceous shale and several sandier horizons, 3 horizons of sideritic concretions
- pale grey fine- to very fine-grained ss, sharp base and top with sideritic horizons, low-angle lamination
- greenish grey pedogenic slts, blocky, massive
- black carbonaceous shale to muddy coal
- greenish grey blocky pedogenic slts, f-up to muddy slts
- pale grey fine- to medium-grained ss, well sorted, uniform, sharp erosive base, sharp flat top, abundant sideritic staining at base, txb, horizontal lamination, low-angle lamination
- black coal
- greenish grey muddy slts, pedogenic, sharp base and top
- dark grey carbonaceous shale, sharp top, more organic rich upward
- greenish grey slts, massive, uniform, blocky, pedogenic, gradational top, poorly exposed

Beynon Ecological Preserve Section



- greenish grey sandy slts. massive, blocky, rubbly, pedogenic

- pale grey fine-grained ss. uniform, well sorted, sharp base and top, low-angle lamination

- greenish grey to grey slts. very sandy, few very fine-grained ss beds, sideritic horizons

- pale grey fine-grained ss. well sorted, uniform, sharp erosional base, sharp top, slightly f-up, low-angle lamination

- greenish grey slts. pedogenic
- pale grey fine-grained ss. sharp base and top

- greenish grey slts. uniform rubbly pedogenic, capped by thin sideritic horizon
- dark grey to black coal. muddy
- greenish grey slts. uniform, massive, blocky, pedogenic

- dark grey to brown carbonaceous shale
- grey silty mudstone. sideritic horizon at top
- greenish grey slts. uniform, blocky, pedogenic
- pale grey very fine-grained ss. sharp base and top, horizontal lamination

- greenish grey shaly slts. blocky, rubbly, pedogenic, uniform, very bentonitic
- black coal, few mudstone horizons
- brown carbonaceous shale

- f-up sequence of thinly interbedded very fine-grained ss and greenish slts. ss:si = 1:1

-greenish grey slts. massive blocky, rubbly, pedogenic, thin very fine-grained ss beds near top, numerous sideritic horizons

- pale grey very fine-grained ss. sharp base, rxl
- greenish grey slts. massive, rubbly, pedogenic
- c-up sequence of thinly interbedded slts and very fine-grained ss. rxl

- greenish grey slts. sandy, f-up, blocky, rubbly, pedogenic

- pale grey to white fine-grained ss. slightly erosive base, f-up, gradational top, low-angle lamination

- brown carbonaceous shale
- dark grey very carbonaceous shale, sharp boundaries
- brown carbonaceous shale, abundant wood fragments

- greenish grey slts. uniform, blocky, rubbly, pedogenic, few thin carbonaceous shales

- greenish grey pedogenic slts. multiple sideritic concretion horizons, one thin carbonaceous shale

- greenish grey slts. slightly f-up, massive, uniform, pedogenic, one thin pale grey bentonite clay near top

- pale grey fine-grained ss. f-up, sharp base with sideritic horizon, gradational top, abundant IHS throughout, and txb

- greenish grey slts. clay rich, massive, uniform, blocky, pedogenic, with several thin laminated clay bands

- brown carbonaceous shale
- greenish grey slts. massive, uniform, pedogenic, abundant wood fragments
- brownish grey carbonaceous shale. thin greenish slts beds in middle
- pale grey very fine-grained ss. c-up, gradational base, sharp top
- brownish grey carbonaceous shale
- pale grey very fine-grained ss. c-up, gradational base, sharp top, low-angle lamination

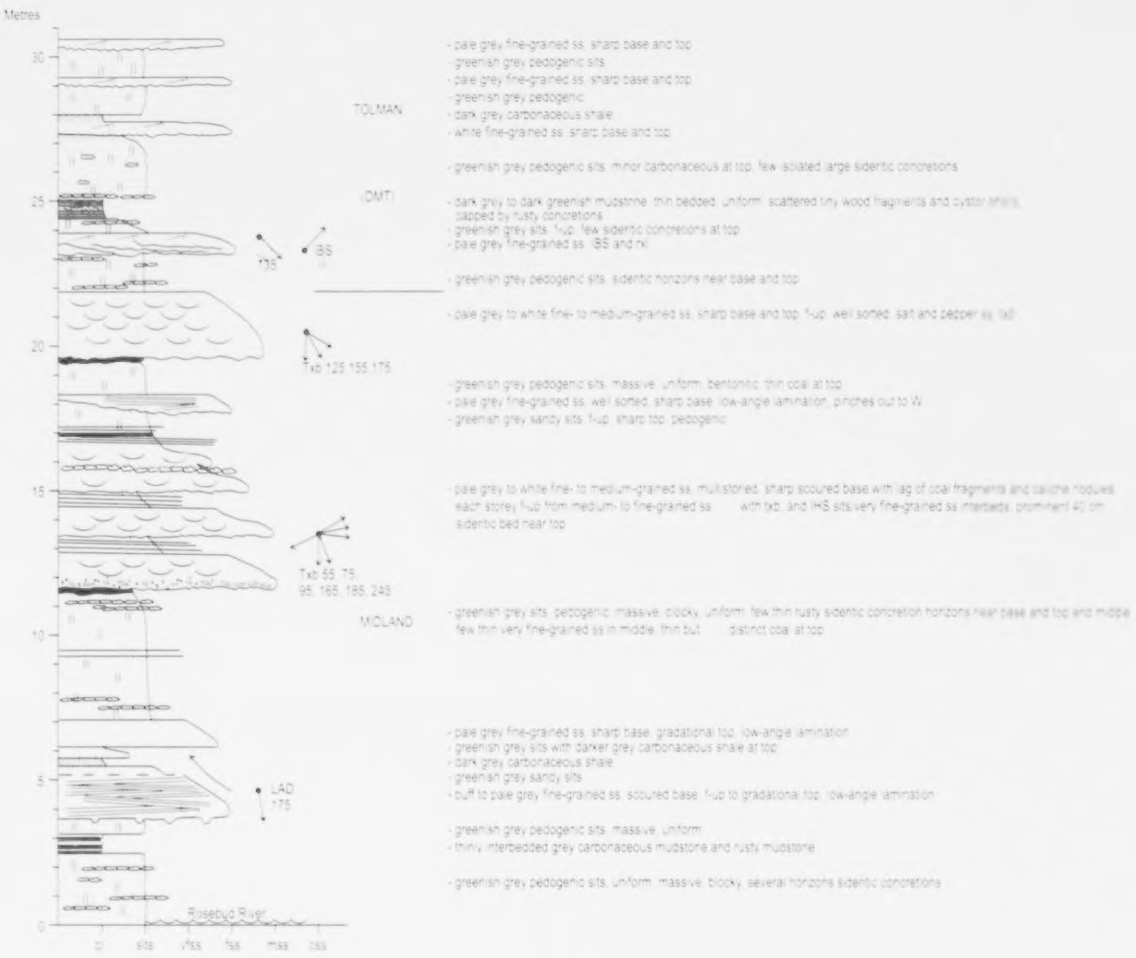
- brownish grey carbonaceous shale
- sideritic concretion horizon, fractured, irregular upper surface
- greenish grey sandy slts. f-up, few ss beds at base, pedogenic
- pale grey very fine- to fine-grained ss. f-up, sharp base, low-angle lamination
- greenish grey pedogenic slts. blocky, massive, uniform

- brown carbonaceous mudstone
- black coal, bituminous subbituminous, sharp boundaries
- greenish grey slts. blocky, uniform, pedogenic, roots at top
- brown carbonaceous mudstone, sharp boundaries

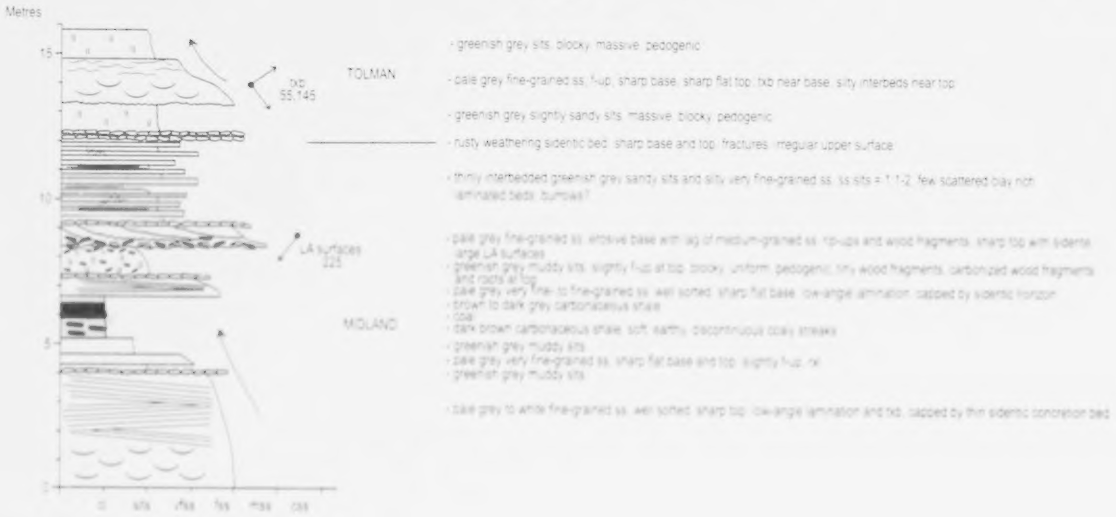
- greenish grey slts. blocky, massive, pedogenic

- pale grey fine-grained ss. well sorted, poor exposure
- black coal

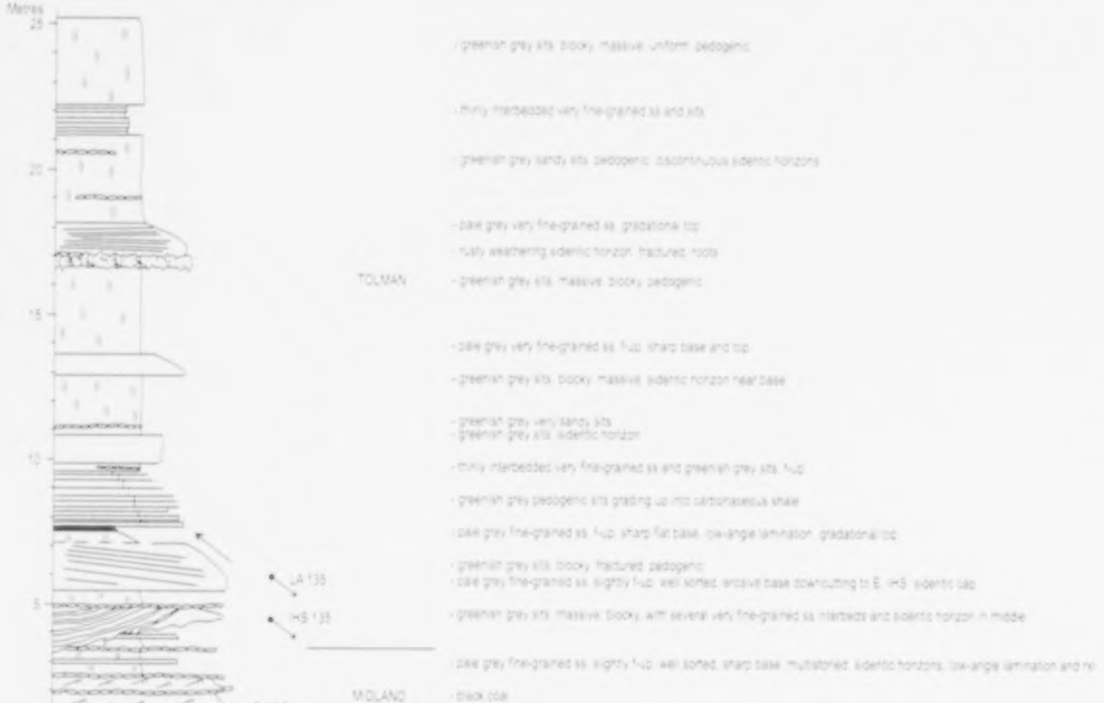
Mile 70.5 Section - Rosebud River


Metres
30
25
20
15
10
5
0
TOLMAN
(DMT)
MIDLAND
135
IBS
Txb 125 155 175
Txb 55, 75,
95, 165, 185, 245
LAD
175
Rosebud River
cl
slts
vfss
fss
mss
css
- pale grey fine-grained ss, sharp base and top
- greenish grey pedogenic slts
- pale grey fine-grained ss, sharp base and top
- greenish grey pedogenic
- dark grey carbonaceous shale
- white fine-grained ss, sharp base and top
- greenish grey pedogenic slts, minor carbonaceous at top, few isolated large sideritic concretions
- dark grey to dark greenish mudstone, thin bedded, uniform, scattered tiny wood fragments and oyster shells,
capped by rusty concretions
- greenish grey slts, f-up, few sideritic concretions at top
- pale grey fine-grained ss, IBS and rxl
- greenish grey pedogenic slts, sideritic horizons near base and top
- pale grey to white fine- to medium-grained ss, sharp base and top, f-up, well sorted, salt and pepper ss, txb
- greenish grey pedogenic slts, massive, uniform, bentonitic, thin coal at top
- pale grey fine-grained ss, well sorted, sharp base, low-angle lamination, pinches out to W
- greenish grey sandy slts, f-up, sharp top, pedogenic
- pale grey to white fine- to medium-grained ss, multistoried, sharp scoured base with lag of coal fragments and caliche nodules
each storey f-up from medium- to fine-grained ss with txb, and IHS slts/very fine-grained ss interbeds, prominent 40 cm
sideritic bed near top
- greenish grey slts, pedogenic, massive, blocky, uniform, few thin rusty sideritic concretion horizons near base and top and middle
few thin very fine-grained ss in middle, thin but distinct coal at top
- pale grey fine-grained ss, sharp base, gradational top, low-angle lamination
- greenish grey slts with darker grey carbonaceous shale at top
- dark grey carbonaceous shale
- greenish grey sandy slts
- buff to pale grey fine-grained ss, scoured base, f-up to gradational top, low-angle lamination
- greenish grey pedogenic slts, massive, uniform
- thinly interbedded grey carbonaceous mudstone and rusty mudstone
- greenish grey pedogenic slts, uniform, massive, blocky, several horizons sideritic concretions

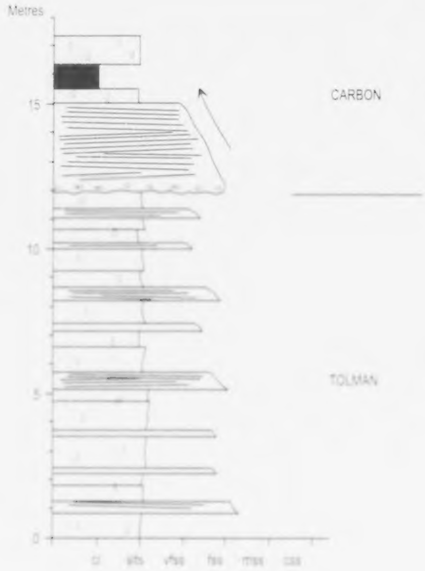
Blue Bridge/Rge Rd 21-2(A) Section


Metres
15
10
5
0
txb
55,145
TOLMAN
LA surfaces
225
MIDLAND
cl
slts
vfss
fss
mss
css
- greenish grey slts, blocky, massive, pedogenic
- pale grey fine-grained ss, f-up, sharp base, sharp flat top, txb near base, silty interbeds near top
- greenish grey slightly sandy slts, massive, blocky, pedogenic
- rusty weathering sideritic bed, sharp base and top, fractures, irregular upper surface
- thinly interbedded greenish grey sandy slts and silty very fine-grained ss, ss:slts = 1:1-2, few scattered clay rich laminated beds, burrows?
- pale grey fine-grained ss, erosive base with lag of medium-grained ss, rip-ups and wood fragments, sharp top with sideritic, large LA surfaces
- greenish grey muddy slts, slightly f-up at top, blocky, uniform, pedogenic, tiny wood fragments, carbonized wood fragments and roots at top
- pale grey very fine- to fine-grained ss, well sorted, sharp flat base, low-angle lamination, capped by sideritic horizon
- brown to dark grey carbonaceous shale
- coal
- dark brown carbonaceous shale, soft, earthy, discontinuous coaly streaks
- greenish grey muddy slts
- pale grey very fine-grained ss, sharp flat base and top, slightly f-up, rxl
- greenish grey muddy slts
- pale grey to white fine-grained ss, well sorted, sharp top, low-angle lamination and txb, capped by thin sideritic concretion bed

Blue Bridge/Rge RD 21-2 (B) Section

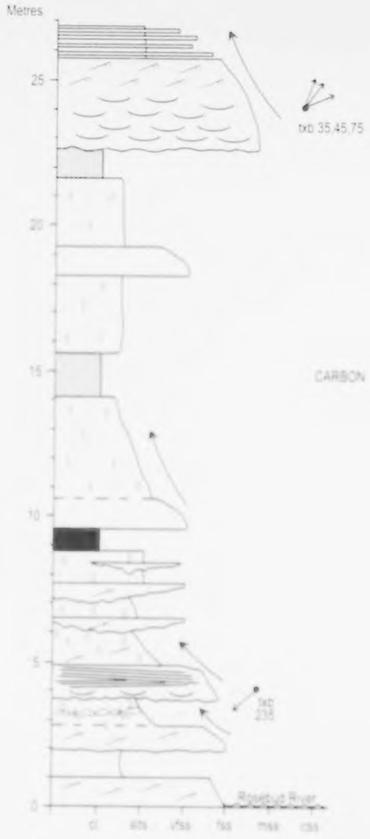

Metres
25
20
15
10
5
0
TOLMAN
LA 135
IHS 135
rxl 85
MIDLAND
cl
slts
vfss
fss
mss
css
- greenish grey slts, blocky, massive, uniform, pedogenic
- thinly interbedded very fine-grained ss and slts
- greenish grey sandy slts, pedogenic, discontinuous sideritic horizons
- pale grey very fine-grained ss, gradational top
- rusty weathering sideritic horizon, fractured, roots
- greenish grey slts, massive, blocky, pedogenic
- pale grey very fine-grained ss, f-up, sharp base and top
- greenish grey slts, blocky, massive, sideritic horizon near base
- greenish grey very sandy slts
- greenish grey slts, sideritic horizon
- thinly interbedded very fine-grained ss and greenish grey slts, f-up
- greenish grey pedogenic slts grading up into carbonaceous shale
- pale grey fine-grained ss, f-up, sharp flat base, low-angle lamination, gradational top
- greenish grey slts, blocky, fractured, pedogenic
- pale grey fine-grained ss, slightly f-up, well sorted, erosive base downcutting to E, IHS, sideritic cap
- greenish grey slts, massive, blocky, with several very fine-grained ss interbeds and sideritic horizon in middle
- pale grey fine-grained ss, slightly f-up, well sorted, sharp base, multistoried, sideritic horizons, low-angle lamination and rxl
- black coal

Mile 74 Section - Rosebud River



- greenish grey slts, pedogenic, massive, rubbly
- black coal
- greenish grey slts, uniform, blocky, rubbly, pedogenic
- pale grey fine-grained ss, slightly f-up, sharp base with sideritic concretions, low-angle laminae
- interbedded thick greenish grey pedogenic slts and thin pale grey very fine- to fine-grained ss, with low-angle lamination, ss:slts = 1:5

Rosebud Section



- greenish to yellowish slts. thin very fine- to fine-grained ss beds

- brown to yellowish brown to greyish fine- to medium-grained ss. well sorted. salt and pepper. sharp erosional base with abundant tiny rip-ups. slightly f-up. sharp top. mostly txb with rxl at top. carbonaceous matter along laminae

- dark grey very uniform slightly silty mudstone. popcorn weathering. bentonitic

- greenish grey silty mudstone. blocky. massive. rubbly. pedogenic. one thick 1 m pale grey very fine-grained ss in middle poorly exposed

- grey to dark grey mudstone. popcorn weathering. bentonitic. very uniform. sharp base and top

- greenish grey sandy slts. slightly f-up to silty mudstone. blocky. rubbly. massive. pedogenic

- grey to buff very fine-grained ss. sharp base. gradational top

- black vitreous coal. sharp base and top

- greenish grey pedogenic slts. includes one 5 m x 50 cm very fine-grained ss lens
- pale grey very fine-grained ss lens. pinchout over 50 m laterally. sharp base and top
- grey to dark grey slts. blocky rubbly. pedogenic
- pale grey very fine-grained ss. discontinuous lens pinches out laterally over 15 m. sharp erosional base. sharp top
- grey silty very fine-grained ss-sandy slts. f-up. blocky. rubbly. pedogenic. minor rxl

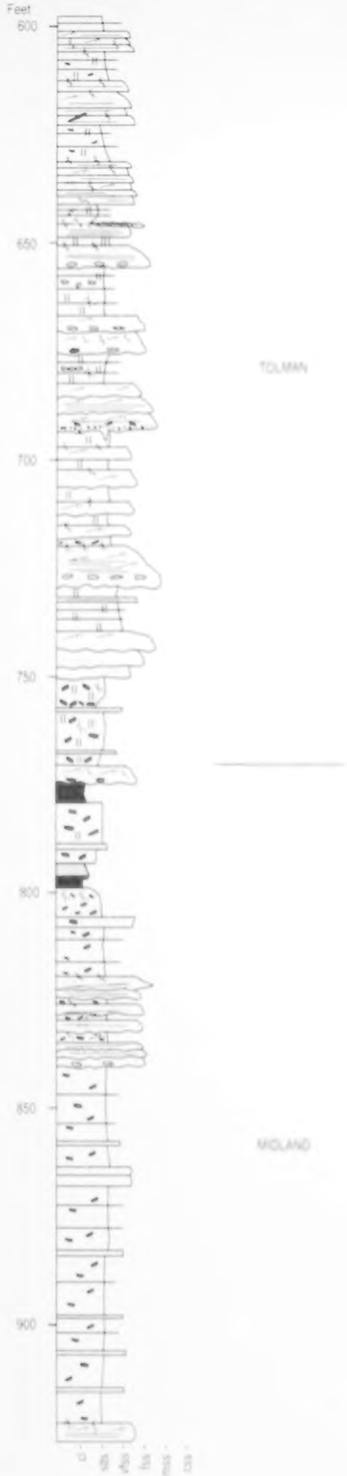
- pale grey fine- to very fine-grained ss. sharp erosional base. slightly f-up. well sorted. gradational top. minor txb. low-angle lamination

- greenish grey sandy slts. f-up. blocky. pedogenic. horizon of large rounded siderite concretions up to 60 cm. with wood fragments and roots
- grey fine-grained ss. slightly f-up. well sorted. sharp base. gradational top. rxl

- greenish grey slts. muddy. poorly exposed

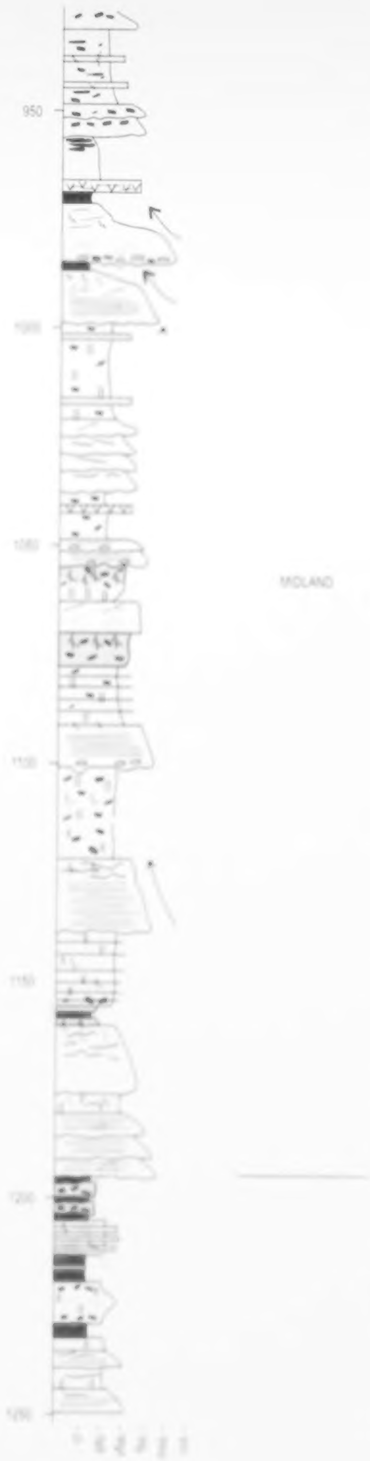
- white fine-grained ss. slightly f-up. well sorted. sharp top. rxl

C.P.O.G. Strathmore 7-12-25-25W4



- greenish grey slts, pedogenic
- grey very fine to fine-grained ss, thin bedded, rippled, burrows
- greenish grey slts, blocky, massive, pedogenic, scattered wood fragments
- grey very fine to fine-grained ss, thin bedded, sharp bases, burrowed tops, horizontal to low-angle lamination and ripples, contorted lamination
- greenish grey slts, blocky, massive, pedogenic, scattered wood fragments
- grey very fine to fine-grained ss in stacked thin beds with sharp bases, burrowed tops, horizontal and low-angle lamination and ripples, coaly fragments, contorted lamination
- greenish grey slts, pedogenic, blocky, scattered wood fragments
- grey fine-grained ss in two thick beds separated by thick sandy slts, ss are f-up, with sharp bases and burrowed tops, horizontal lamination, minor ripples, sideritic horizon at top
- greenish grey to brownish grey slts, pedogenic, roots, sideritic concretions
- grey fine-grained ss in several thick beds, sharp bases, ripples
- greenish grey to brownish grey slts, pedogenic, roots, sideritic concretions
- stacked beds of fine-grained ss in fining-upward units, each with sharp bases and low-angle lamination and rippled tops, sharp erosional base has layer of coarse sand grains which fill deep fractures in underlying unit, and wood fragments, minor burrows
- thickly interbedded greenish grey slts and grey very fine to fine-grained ss, carbonaceous and rooted at base, slts are pedogenic, contorted lamination, rooting, ripples, burrows
- grey very fine to fine-grained ss, fining upward, sharp base with rip-ups and contorted lamination, low-angle lamination, minor ripples, roots
- greenish grey sandy slts, massive, blocky, pedogenic, few thin beds of very fine-grained ss with low-angle lamination
- stacked grey very fine to fine-grained ss beds separated by thin silty beds, slightly c-up, contorted lamination lower part, rip-ups and ripples in upper bed
- greenish grey sandy slts, massive, blocky, pedogenic, abundant scattered wood fragments, some roots, several thin sandy streaks, darker coloured and finer grained and more carbonaceous at base and near top
- grey very fine to fine-grained ss, f-up, sharp base with rip-ups, ripples and burrows and carbonaceous fragments at top
- coal
- greenish grey sandy slts, carbonaceous at base, thin sandy zone in middle, scattered wood fragments, likely pedogenic
- coal and thin carbonaceous mudstone
- greenish grey slts to sandy slts with several sandy streaks and thicker fine-grained ss bed, scattered wood fragments, very carbonaceous and rooted at top
- stack of very fine- to fine-grained ss beds separated by thin units of sandy slts, each ss bed is f-up from sharp erosional base with rip-ups to low-angle lamination to contorted lamination with burrows at tops, slts have wood fragments
- dark grey to greenish grey slts with numerous thin to thick beds of silty very fine to fine-grained ss, carbonaceous, wood fragments
- grey fine-grained ss, sharp base, carbonaceous streaks, ripples and roots at top, low-angle lamination

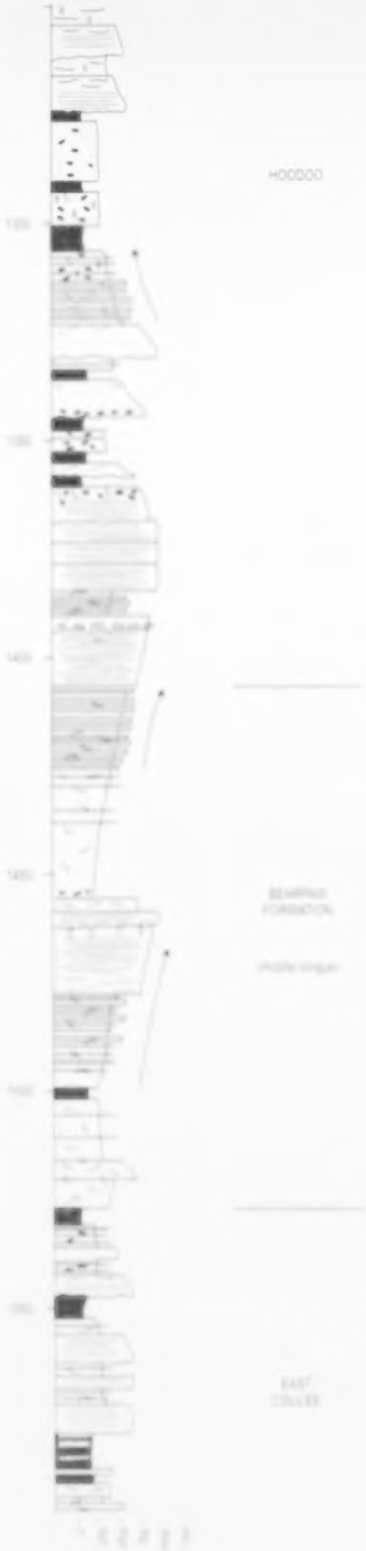
C.P.O.G. Strathmore 7-12-25-25W4 cont.



- grey very fine-grained ss. f-up to carbonaceous slts, wood fragments
- grey to greenish grey sandy slts with thin silty very fine-grained ss beds. abundant wood fragments and coaly streaks. burrowing
- grey stacked very fine to fine-grained ss. sharp bases and tops, contorted lamination. wood fragments, sideritic concretions
- dark greenish grey mudstone, uniform, coaly streaks at top
- light grey fine-grained ss. f-up, bentonitic horizon
- coal and carbonaceous shale
- grey medium ss f-up to greenish grey slts. sharp erosive base with rip-ups and wood fragments and contorted lamination, minor burrowing near top
- coal and carbonaceous shale
- grey fine-grained ss f-up to muddy slts with roots, sharp base, lower part massive, low-angle lamination to rippled top, minor burrows
- greenish grey slts, pedogenic, scattered wood fragments, massive, blocky, with minor sandy zones near top and bottom
- stacked grey very fine- to fine-grained ss beds, each with sharp erosional base and f-up, minor ripples and carbonaceous streaks
- dark grey muddy slts, very carbonaceous, abundant wood fragments, one thin pale green bentonite
- grey fine-grained ss, thick bedded, sharp bases with rip-ups, low-angle lamination
- greenish grey pedogenic slts, grading up into dark grey sandy slts, roots and wood fragments at top
- grey very fine- to fine-grained ss, contorted lamination, rippled top
- dark grey very carbonaceous slts, sandy, rooted
- grey slts with minor very fine-grained ss beds, pedogenic, minor wood fragments
- light grey fine-grained ss, uniform, well sorted, sharp base with rip-ups, low-angle lamination, minor burrows at top
- greenish grey pedogenic slts, wood fragments, rooted zones
- light grey very fine- to fine-grained ss, f-up, uniform, well sorted, sharp base, low-angle lamination, silty streaks and roots at top
- grey pedogenic slts with minor very fine-grained ss silty ss beds, roots, carbonaceous fragments near base
- coal and carbonaceous shale, roots, wood fragments
- dark grey silty very fine-grained ss, sharp base, silty streaks, burrows
- dark grey sandy slts, pedogenic
- light grey fine-grained ss, thick bedded, sharp bases, low-angle lamination, some contorted lamination at bases
- coal and carbonaceous slts
- thinly interbedded slts and very fine-grained ss, abundant burrows and contorted lamination
- coal and carbonaceous shale
- grey to dark grey sandy slts and mudstone, sandy, middle zone has contorted lamination, wood fragments, pedogenic
- coal

thickly interbedded grey sandy slts and fine-grained ss; ss beds are sharp-based and f-up with low-angle lamination, slts are pedogenic and have coaly streaks

C.P.O.G. Strathmore 7-12-25-25W4 cont.



- dark grey carbonaceous shale and silty shale, wood fragments

- coal
- grey pedogenic slts, massive, blocky, slickensides, wood fragments and roots, coaly streaks

- coal

- grey f-up succession of sharp-based fine-grained ss with ripples, to thinly interbedded very fine-grained ss and sandy slts with minor burrowing, to slts with very fine-grained ss streaks and abundant wood fragments

- grey slts, thin very fine-grained ss bed
- coal

- grey fine- to medium-grained ss, f-up, sharp base with rip-ups and coaly wood fragments, contorted lamination and burrows at top
- coal
- brownish grey sandy slts, abundant coaly fragments
- coal
- brownish grey fine-grained ss, sharp base, ripples, coaly fragments, f-up
- coal
- light grey fine-grained ss, well sorted, uniform, low-angle lamination, sharp base and top, abundant coaly fragments and roots at top

- light grey fine-grained ss, well sorted, uniform, thick-bedded, sharp base and top, horizontal and low-angle lamination throughout

- dark grey thinly interbedded slts and very fine-grained ss, sharp based f-up beds, horizontal burrows

- light grey very fine- to fine-grained ss, well sorted, uniform, slightly c-up, sharp base and top, horizontal and low-angle lamination, thin horizon of rip-ups near top

- dark grey thinly interbedded slts and very fine-grained ss, c-up trend, burrowing decreases upward, beds sharp based with horizontal lamination and gradational tops

- dark grey silty mudstone, slight c-up trend, abundant tiny horizontal burrows throughout, sharp base with abundant coaly wood fragments, few very thin sils beds toward top

- grey silty fine-grained ss, thoroughly bioturbated

- dark grey to grey, fine- to medium-grained ss, slight c-up trend, thin silty interbeds in lower half, abundant horizontal and low-angle lamination, near top is sharp surface with siderite concretions and rip-ups, underlain by abundant large vertical burrows

- thinly interbedded grey slts and very fine-grained ss, cleaner up and thickening upward, abundant small horizontal burrows

- dark grey very carbonaceous shale to coal

- dark grey silty mudstone, few thin slts beds, bioturbated

- dark grey silty fine-grained ss, f-up, bioturbated including large vertical burrows at base

- dark grey sandy slts, thoroughly bioturbated
- coal
- grey thinly interbedded slts and very fine-grained ss, abundant carbonaceous fragments, one thicker very fine-grained ss bed

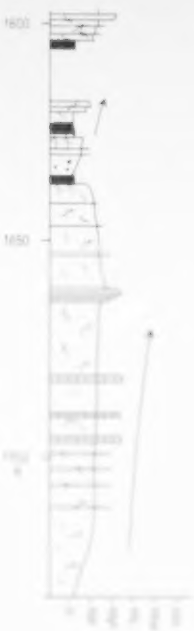
- grey very fine- to fine-grained ss, sharp base, horizontal lamination and ripples
- thin coal grading up into dark grey carbonaceous silty mudstone

- thinly interbedded grey fine-grained ss and sandy slts, minor burrowing, horizontal lamination

- dark grey carbonaceous shale to coal

- dark grey carbonaceous shale

C.P.O.G. Strathmore 7-12-25-25W4 cont.



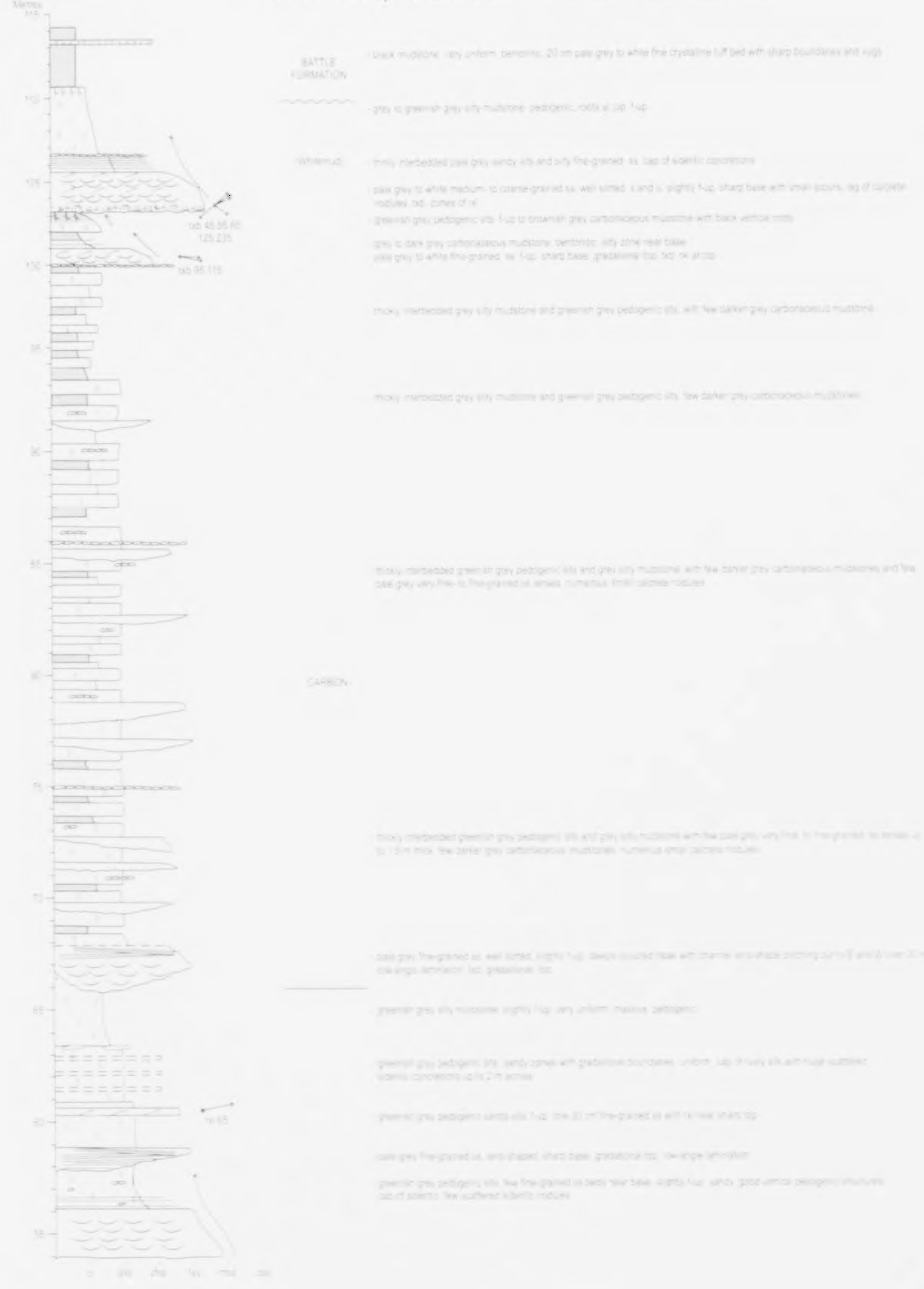
- grey interbedded slts and thin very fine- to fine-grained ss, abundant burrowing, ss beds sharp based
- coal
- c-up sequence of dark grey carbonaceous shale to grey sandy slts, wood fragments, bioturbation, rooting?
- coal
- grey silty shale, thin slts beds in middle, rooted top, tiny vitreous organic fragments
- carbonaceous shale to coal, sharp base, gradational top
- grey silty claystone, burrowed, with thin very fine-grained ss to slts beds, rooted at top
- grey, thin bedded very fine- to fine-grained ss, well bioturbated
- grey silty mudstone with thin sideritic beds up to 10 cm thick, burrowed

BEARPAW FORMATION

- grey to dark grey silty mudstone, burrowed, slightly c-up, thin burrowed very fine-grained ss beds toward top

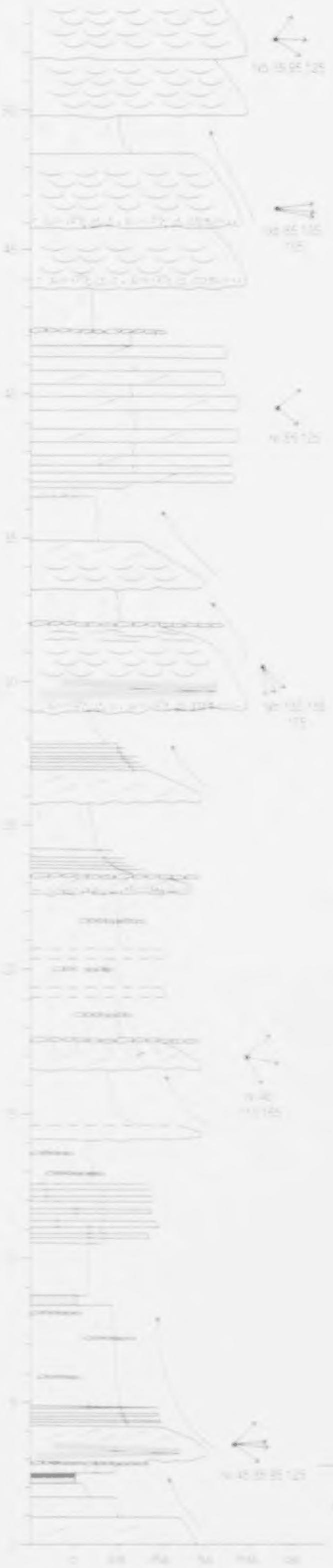
(lower tongue)

Power Line/Twp Rd 32-2 Section - Red Deer River, East Side



- black mudstone, very uniform, bentonitic; 20 cm pale grey to white fine crystalline tuff bed with sharp boundaries and vugs
- grey to greenish grey silty mudstone, pedogenic, roots at top, f-up
- thinly interbedded pale grey sandy slts and silty fine-grained ss; cap of sideritic concretions
- pale grey to white medium- to coarse-grained ss, well sorted, x and xl, slightly f-up, sharp base with small scours, lag of calcrete nodules, bd, zones of rxl
- greenish grey pedogenic slts f-up to brownish grey carbonaceous mudstone with black vertical roots
- grey to dark grey carbonaceous mudstone, bentonitic, silty zone near base
- pale grey to white fine-grained ss, f-up, sharp base, gradational top, bd, rxl at top
- thickly interbedded grey silty mudstone and greenish grey pedogenic slts, with few darker grey carbonaceous mudstone
- thickly interbedded grey silty mudstone and greenish grey pedogenic slts, few darker grey carbonaceous mudstones
- thickly interbedded greenish grey pedogenic slts and grey silty mudstone, with few darker grey carbonaceous mudstones and few pale grey very fine- to fine-grained ss lenses, numerous small calcrete nodules
- thickly interbedded greenish grey pedogenic slts and grey silty mudstone with few pale grey very fine- to fine-grained ss lenses up to 1.5 m thick, few darker grey carbonaceous mudstones, numerous small calcrete nodules
- pale grey fine-grained ss, well sorted, slightly f-up, deeply scoured base with channel lens shape pinching out to E and W over 20 m, low angle lamination, bd, gradational top
- greenish grey silty mudstone, slightly f-up, very uniform, massive, pedogenic
- greenish grey pedogenic slts, sandy zones with gradational boundaries, uniform, cap of rusty slts with huge scattered sideritic concretions up to 2 m across
- greenish grey pedogenic sandy slts f-up, one 30 cm fine-grained ss with rxl near sharp top
- pale grey fine-grained ss, lens shaped, sharp base, gradational top, low-angle lamination
- greenish grey pedogenic slts, few fine-grained ss beds near base, slightly f-up, sandy, good vertical pedogenic structures, cap of sideritic, few scattered sideritic nodules

Power Line/Twp Rd 32-2 Section - Red Deer River, East Side cont.



pale grey fine- to medium-grained ss, well sorted, slightly f-up, multistoried, txb (prominent ss halfway up cliff with hoodoo like topography)

greenish grey pedogenic slts, uniform, massive

pale grey fine- to medium-grained ss, well sorted, slightly f-up, multistoried, txb, calcite nodule rip-ups (prominent ss halfway up cliff)

greenish grey pedogenic silty mudstone, very uniform, bentonitic

thickly interbedded greenish grey sandy slts and pale grey fine- to medium-grained ss, ss:slts = 1:1, thin cap of sideritic concretions, rxl

pale greenish white bentonite claystone, sharp boundaries

TOLMAN

greenish grey silty mudstone, bentonitic, uniform

pale grey fine-grained ss, f-up, sharp base, txb, rxl

greenish grey pedogenic slts, very uniform

pale grey fine- to medium-grained ss, well sorted, f-up, scoured base with lag of calcite nodules, few silty beds at top, low-angle lamination, txb, cap of sideritic concretions with sharp top

greenish grey silty mudstone, slightly f-up, very uniform

pale grey fine-grained ss with sharp base passing up into thinly interbedded greenish grey slts and very fine-grained ss, rxl

greenish grey pedogenic slts, f-up, numerous thin very fine-grained ss beds near base

pale grey fine-grained ss, silty, sharp base with rip-ups of silty carbonaceous shale, rxl, cap of sharp-topped siderite

greenish grey pedogenic slts, few 50 cm pale grey very fine- to fine-grained ss beds with gradational boundaries, few thin sideritic horizons

pale grey fine-grained ss, well sorted, scoured base, slightly f-up, roots, rxl, cap of siderite with gradational base and sharp irregular top

greenish grey muddy slts, f-up, uniform

pale grey fine-grained ss, well sorted, sharp base, gradational top, low-angle lamination

greenish grey silty mudstone, very uniform, massive, several thin sandy sideritic horizons

thickly interbedded greenish grey silty mudstone and pale grey silty very fine-grained ss with gradational boundaries, ss:slts = 1:1

greenish grey pedogenic silty mudstone, uniform, massive

greyish brown mudstone, slightly carbonaceous

greenish grey pedogenic slts, massive, uniform, few thin very fine-grained ss beds near base, few thin sideritic horizons throughout

pale grey fine-grained ss, well sorted, scoured base, gradational top, f-up, low-angle lamination, rxl

greenish grey pedogenic slts, capped by thin siderite
dark grey carbonaceous mudstone, grading up into black lignitic coal
grey mudstone, f-up, horizontal lamination, gradational top
greenish grey pedogenic slts, massive, uniform

MIDLAND

pale grey fine-grained ss, well sorted, rxl

Appendix B
Horseshoe Canyon Formation subsurface tops

Well location	ft. or m	Top BLRV	Top low BRPW	Isop low BRPW	Top STHM	Isop STHM	Top mid BRPW	Isop mid BRPW	Top HDOO	Isop HDOO	Top upp BRPW	Isop upp BRPW	Top MDLD	Isop MDLD	Top DMT	Isop DMT	Top TLMN	Isop TLMN	Top CRBN	Isop CRBN
7-2-20-29W4	ft.	3460	3360	100	3200	160	3180	20	2770	410	2770	0	2255	515	2240	15	1995	245	1690	305
8-1-20-28W4	m	875	842	33	811	31	780	31	666	114	666	0	520	146	515	5	425	90	340	85
14-9-20-27W4	m	830	797	33	763	34	735	28	626	109	626	0	475	151	469	6	392	77	291	101
7-1-20-26W4	ft.	2090	1942	148	1860	82	1700	160	1440	260	1432	8	883	549	860	23	570	290		
11-18-20-25W4	ft.	2150	1992	158	1905	87	1764	141	1526	238	1515	11	955	560	940	15	657	283		
14-4-20-24W4	m	590	550	40	530	20	468	62	393	75	391	2	228	163	220	8				
14-9-20-23W4	m	550	518	32	498	20	400	98	350	50	345	5	198	147	186	12				
6-18-20-22W4	m	503	468	35	455	13	335	120	302	33	291	11	<185	106+	<185					
1-18-20-21W4	m	302	<185	117+																
7-22-20-20W4	ft.	1000	<600	400+																
10-6-20-19W4	ft.	937	<500	500+																
7-35-21-29W4	ft.	2750	2630	120	2610	20	2415	195	2088	327	2088	0	1610	478	1600	10	1295	305		
10-18-21-28W4	ft.	2910	2780	130	2670	110	2540	130	2260	280	2260	0	1808	452	1800	8	1500	300	1220	280
6-9-21-27W4	m	808	771	37	740	31	712	28	605	107	600	5	460	140	455	5	370	85		
10-27-21-26W4	ft.	1915	1820	95	1720	100	1590	130	1293	297	1270	23	850	420	835	15	<600	235+		
7-16-21-25W4	ft.	1770	1655	115	1545	110	1370	175	1125	245	1100	25	700	400	680	20	425	255		
6-6-21-24W4	m	520	478	42	468	10	400	68	317	83	305	12	193	112	186	7				
8-7-21-23W4	m	440	392	48	392	0	318	74	235	83	215	20								
13-25-21-22W4	m	340	275	65	275	0	190	85												
10-13-21-21W4	m	272	215	57	215	0														
6-3-21-20W4	m	263	208	55	208	0														
7-31-21-19W4	ft.	710	550	160	550	0														
11-10-22-29W4	ft.	2893	2800	93	2625	175	2570	55	2145	425	2145	0	1650	495	1650	0	1340	310		
10-27-22-28W4	m	777	746	31	706	40	672	34	585	87	580	5	430	150	428	2	340	88	250	90
8-1-22-27W4	m	666	632	34	588	44	550	38	470	80	466	4	322	144	320	2	248	72	155	93
4-25-22-26W4	m	620	581	39	540	41	502	38	425	77	422	3	290	132	285	5	215	70		
6-19-22-25W4	m	597	550	47	522	28	481	41	411	70	406	5	268	138	261	7	194	67		
10-33-22-24W4	ft.	1700	1540	160	1490	50	1315	175	1100	215	1085	15	655	430	630	25				
7-25-22-23W4	ft.	1415	1230	185	1205	25	975	230	795	180	775	20	<550	225+	<550					
6-28-22-21W4	m	387	345	42	337	8	246	91												
6-10-22-20W4	ft.	915	785	130	785	0	520	265												
7-9-22-19W4	ft.	740	625	115	625	0														
16-35-23-29W4	ft.	2970	2870	100	2775	95	2660	115	2270	390	2270	0	1675	595	1675	0	1450	225	1200	250
14-27-23-28W4	m	805	775	30	742	33	700	42	612	88	610	2	445	165	442	3	353	89	282	71
2-18-23-26W4	m	693	661	32	627	34	592	35	507	85	495	12	377	118	373	4	290	83	215	75
13-19-23-25W4	m	640	607	33	567	40	530	37	459	71	443	16	320	123	312	8	251	61		
10-10-23-23W4	ft.	1610	1485	125	1390	95	1235	155	980	255										
10-6-23-19W4	ft.	890	715	175	715	0														
11-27-24-29W4	ft.	3268	3230	38	2950	280	2930	20	2470	460	2470	0	1890	580	1890	0	1640	250	1490	150
6-2-24-29W4	m	933	917	16	840	77	822	18	692	130	692	0	535	157	535	0	470	65	385	85
8-4-24-28W4	m	856	840	16	777	63	757	20	635	122	635	0	489	146	489	0	400	89	315	85
10-7-24-27W4	ft.	2480	2360	120	2240	120	2145	95	1820	325	1820	0	1365	455	1358	7	1100	258	850	250
11-23-24-26W4	ft.	2077	1950	127	1840	110	1730	110	1480	250	1480	0	1020	460	1000	20	760	240		
10-15-24-25W4	ft.	1960	1855	105	1728	127	1605	123	1400	205	1400	0	955	445	930	25	720	210		
16-1-24-24W4	m	500	470	30	424	46	381	43	323	58	323	0	190	133						
6-6-24-23W4	m	490	455	35	425	30	376	49	310	66	310	0								

Appendix B

Horseshoe Canyon Formation subsurface tops

Well location	ft. or m	Top BLRV	Top low BRPW	Isop low BRPW	Top STHM	Isop STHM	Top mid BRPW	Isop mid BRPW	Top HDOO	Isop HDOO	Top upp BRPW	Isop upp BRPW	Top MDLD	Isop MDLD	Top DMT	Isop DMT	Top TLMN	Isop TLMN	Top CRBN	Isop CRBN
13-32-24-21W4	ft.	1180	1065	115	975	90	820	155	565	255	565	0								
10-36-24-19W4	ft.	1100	910	190	885	25	730	155	510	220	485	25								
10-36-24-18W4	ft.	992	780	212	760	20	590	170												
7-16-24-17W4	ft.	600																		
16-7-24-16W4	ft.	520																		
11-23-25-29W4	ft.	3155	3140	15	2915	225	2895	20	2550	345	2550	0	1975	575	1975	0	1715	260	1505	210
11-31-25-28W4	ft.	3100	3080	20	2870	210	2820	50	2540	280	2540	0	1980	560	1980	0	1700	280	1500	200
11-36-25-27W4	ft.	2240	2205	35	2000	205	1938	62	1695	243	1695	0	1165	530	1165	0	860	305		
6-11-25-26W4	ft.	2005	1922	83	1775	147	1680	95	1450	230	1450	0	1000	450	1000	0				
7-12-25-25W4	ft.	1730	1660	70	1525	135	1390	135	1195	195	1195	0	775	420	770	5	490	280	370	120
8-11-25-24W4	m	541	525	16	475	50	433	42	368	65	368	0	237	131	235	2				
6-36-25-23W4	m	437	407	30	370	37	325	45	255	70	255	0	142	113	128	14				
6-23-25-22W4	m	427	395	32	358	37	327	31	239	88	239	0	<160	79+						
10-36-25-21W4	ft.	1295	1082	213	1060	22	845	215	635	210	635	0	<450	185+						
11-33-25-20W4	m	415	350	65	350	0	262	88	220	42	213	7	100	113						
11-36-25-19W4	ft.	1465	1255	210	1255	0	945	310	875	70	790	85	<550							
10-2-25-18W4	ft.	980	820	160	820	0	<450	370+												
11-21-25-17W4	ft.	910	750	160	750	0														
7-3-26-29W4	ft.	3355	3355	0	3090	265	3090	0	2665	425	2665	0	2080	585	2080	0	1820	260	1602	218
11-18-26-28W4	ft.	3215	3215	0	2980	235	2980	0	2575	405	2575	0	2045	530	2045	0	1765	280	1550	215
10-22-26-27W4	ft.	2372	2350	22	2135	215	2135	0	1765	370	1765	0	1300	465	1300	0	1010	290		
6-4-26-25W4	ft.	1975	1940	35	1750	190	1730	20	1368	362	1368	0	970	398	970	0	720	250		
6-16-26-24W4	ft.	1755	1685	70	1530	155	1440	90	1160	280	1160	0	765	395	755	10				
10-31-26-23W4	ft.	1790	1700	90	1555	145	1440	115	1185	255	1185	0	820	365	810	10	<600	210+		
6-28-26-22W4	ft.	1360	1270	90	1130	140	1030	100	770	260	770	0	460	310						
6-36-26-21W4	m	385	350	35	316	34	275	41	200	75	200	0								
6-13-26-20W4	m	432	392	40	355	37	312	43	235	77	233	2								
6-17-26-19W4	m	422	383	39	345	38	306	39	235	71	227	8	140	87	121					
6-25-26-18W4	m	370	315	55	305	10	218	87	185	33	120	65								
10-16-26-17W4	ft.	950	740	210	740	0														
6-33-26-16W4	m	242	188	54	188	0														
16-29-26-15W4	m	225	175	50	175	0														
7-3-26-29W4	ft.	3355	3355	0	3090	265	3090	0	2665	425	2665	0	2080	585	2080	0	1820	260	1602	218
11-18-26-28W4	ft.	3215	3215	0	2980	235	2980	0	2575	405	2575	0	2045	530	2045	0	1765	280	1550	215
10-22-26-27W4	ft.	2372	2350	22	2135	215	2135	0	1765	370	1765	0	1300	465	1300	0	1010	290		
6-4-26-25W4	ft.	1975	1940	35	1750	190	1730	20	1368	362	1368	0	970	398	970	0	720	250		
6-16-26-24W4	ft.	1755	1685	70	1530	155	1440	90	1160	280	1160	0	765	395	755	10				
10-31-26-23W4	ft.	1790	1700	90	1555	145	1440	115	1185	255	1185	0	820	365	810	10	<600	210+		
6-28-26-22W4	ft.	1360	1270	90	1130	140	1030	100	770	260	770	0	460	310						
6-36-26-21W4	m	385	350	35	316	34	275	41	200	75	200	0								
6-13-26-20W4	m	432	392	40	355	37	312	43	235	77	233	2								
6-17-26-19W4	m	422	383	39	345	38	306	39	235	71	227	8	140	87	121					
6-25-26-18W4	m	370	315	55	305	10	218	87	185	33	120	65								
10-16-26-17W4	ft.	950	740	210	740	0														
6-33-26-16W4	m	242	188	54	188	0														
16-29-26-15W4	m	225	175	50	175	0														

Appendix B
Horseshoe Canyon Formation subsurface tops

Well location	ft. or m	Top BLRV	Top low BRPW	Isop low BRPW	Top STHM	Isop STHM	Top mid BRPW	Isop mid BRPW	Top HDOO	Isop HDOO	Top upp BRPW	Isop upp BRPW	Top MDLD	Isop MDLD	Top DMT	Isop DMT	Top TLMN	Isop TLMN	Top CRBN	Isop CRBN
10-35-27-29W4	ft.	3448	3448	0	3185	263	3170	15	2800	370	2800	0	2385	415	2385	0	2020	365	1845	175
7-19-27-28W4	ft.	3295	3295	0	3075	220	3035	40	2680	355	2680	0	2320	360	2320	0	1950	370	1760	190
7-15-27-27W4	ft.	2460	2440	20	2230	210	2195	35	1870	325	1870	0	1495	375	1495	0	1177	318	1020	157
6-35-27-24W4	m	523	503	20	453	50	429	24	340	89	340	0	235	105	233	2	140	93		
6-31-27-23W4	m	485	465	20	415	50	389	26	305	84	305	0	202	103	200	2				
10-5-27-22W4	ft.	1360	1260	100	1120	140	1000	120	765	235	765	0								
1-23-27-21W4	ft.	1130	1025	105	900	125	780	120	570	210	555	15	240	315						
12-15-27-20W4	m	334	302	32	260	42	221	39												
14-30-27-19W4	m	319	283	36	252	31														
8-27-27-18W4	m	252	212	40	203	9	98	105	77	21										
6-25-27-17W4	m	340	292	48	292	0														
6-34-27-16W4	ft.	1010	850	160	850	0														
6-20-27-15W4	m	256	203	53	203	0														
7-3-28-29W4	ft.	3418	3418	0	3120	298	3120	0	2790	330	2790	0	2370	420	2370	0	2025	345	1842	183
11-29-28-28W4	ft.	2977	2970	7	2720	250	2710	10	2390	320	2390	0	1983	407	1983	0	1660	323	1457	203
6-20-28-27W4	ft.	2622	2610	12	2390	220	2370	20	2025	345	2025	0	1618	407	1618	0	1333	285	1100	233
11-31-28-26W4	ft.	2330	2310	20	2110	200	2070	40	1735	335	1735	0	1305	430	1305	0	1045	260		
10-11-28-25W4	ft.	1918	1892	26	1680	212	1632	48	1335	297	1335	0	915	420	915	0	655	260	420	235
6-10-28-24W4	m	545	525	20	467	58	451	16	368	83	368	0	234	134	234	0				
5-29-28-23W4	m	500	477	23	427	50	405	22	321	84	321	0	204	117	200	4	125	75		
10-7-28-22W4	ft.	1463	1362	101	1200	162	1125	75	890	235	890	0	500	390	470	30				
6-15-28-21W4	m	376	350	26	308	42	277	31												
8-26-28-19W4	m	294	264	30	228	36														
6-15-28-18W4	m	267	218	49	197	21														
3-33-28-17W4	m	375	315	60	300	15	230	70												
16-36-28-16W4	m	343	285	58	271	14														
11-18-28-15W4	ft.	1030	820	210	795	25	530	265	505	25										
8-10-29-29W4	m	1023	1019	4	945	74	945	0	818	127	818	0	700	118	700	0	610	90	540	70
11-16-29-28W4	m	948	943	5	867	76	865	2	745	120	745	0	632	113	632	0	550	82	475	75
11-6-29-27W4	m	848	836	12	765	71	760	5	657	103	657	0	542	115	542	0	455	87	375	80
16-32-29-26W4	m	699	688	11	615	73	606	9	505	101	505	0	408	97	408	0	325	83		
16-24-29-25W4	ft.	1770	1720	50	1495	225	1465	30	1155	310	1155	0	840	315	840	0				
14-31-29-24W4	ft.	1805	1780	25	1550	230	1520	30	1195	325	1195	0	855	340	855	0	610	245		
13-20-29-23W4	ft.	1580	1535	45	1355	180	1250	105	995	255	980	15	650	330	640	10	370	270	190	180
7-27-29-22W4	ft	1350	1220	130	1100	120	985	115	760	225	730	30	405	325						
10-18-29-21W4	ft.	1170	1085	85	950	135	840	110	605	235										
6-20-29-20W4	ft.	1060	945	115	838	107	680	158	460	220										
6-25-29-19W4	m	288	240	48	218	22														
12-36-29-18W4	m	350	295	55	285	10	218	67	190	28	177	13								
16-28-29-17W4	m	515	458	57	447	11	375	72	361	14	340	21	243	97	224	19				
14-32-29-16W4	m	426	362	64	358	4	274	84	267	7	245	22								
6-15-29-15W4	m	360	300	60	290	10	210	80	200	10										
11-36-30-29W4	m	919	919	0	830	89	830	0	732	98	732	0	603	129	603	0	515	88	443	72
8-6-30-28W4	m	909	901	8	825	76	825	0	712	113	712	0	609	103	609	0	520	89	453	67
6-4-30-27W4	ft.	2590	2565	25	2335	230	2335	0	1970	365	1970	0	1605	365	1605	0	1330	275	1110	220
6-11-30-26W4	ft.	2030	1995	35	1785	210	1785	0	1445	340	1445	0	1090	355	1090	0	820	270		
10-33-30-25W4	m	627	615	12	560	55	550	10	445	105	445	0	329	116	329	0	255	74	175	80
6-25-30-24W4	ft.	1675	1650	25	1460	190	1412	48	1130	282	1130	0	745	385	745	0				

Appendix B

Horseshoe Canyon Formation subsurface tops

Well location	ft. or m	Top BLRV	Top low BRPW	Isop low BRPW	Top STHM	Isop STHM	Top mid BRPW	Isop mid BRPW	Top HDOO	Isop HDOO	Top upp BRPW	Isop upp BRPW	Top MDLD	Isop MDLD	Top DMT	Isop DMT	Top TLMN	Isop TLMN	Top CRBN	Isop CRBN
10-15-30-23W4	m	450	440	10	382	58	368	14	288	80	288	0	160	128	160	0				
6-6-30-22W4	m	455	436	19	384	52	369	15	295	74	295	0	<180	115+	<180	0				
8-18-30-21W4	m	369	351	18	300	51	272	28	<220	52+										
8-31-30-20W4	m	350	327	23	284	43	254	30	195	59										
8-2-30-19W4	m	300	258	42	240	18	190	50												
10-18-30-18W$	ft.	1125	980	145	930	50	695	235	630	65	[illegible]	10	240	380	210	30				
12-11-30-17W4	m	520	463	57	453	10	385	68	362	23	349	13	251	98	233	18				
14-30-30-16W4	m	343	285	58	276	9	207	69	185	22										
10-7-30-15W4	m	369	310	59	301	9	226	75	212	14	156	56								
7-36-31-29W4	ft.	3040	3040	0	2790	250	2790	0	2430	360	2430	0	2035	395	2035	0	1715	320	1530	185
11-8-31-28W4	m	898	895	3	825	70	825	0	718	107	718	0	602	116	602	0	498	104	445	53
7-11-31-27W4	m	734	727	7	669	58	669	0	560	109	560	0	445	115	445	0	357	88	304	53
16-31-26W4	m	701	698	3	635	63	633	2	521	112	521	0	404	117	404	0	325	79	270	55
11-28-31-25W4	ft.	2250	2228	22	2015	213	2000	15	1720	280	1720	0	1305	415	1305	0	1030	275	870	160
12-4-31-24W4	m	592	584	8	524	60	519	5	435	84	435	0	315	120	315	0	216	99		
11-30-31-23W4	ft.	1780	1755	25	1570	185	1525	45	1270	255	1270	0	870	400	870	0	580	290		
14-11-31-22W4	m	396	389	7	324	65	320	4	240	80	240	0								
6-21-31-21W4	m	366	349	17	296	53	273	23	215	58	215	0								
1-18-31-20W4	m	384	358	26	312	46	285	27	232	53	232	0								
9-31-31-19W4	m	356	335	21	285	50	256	29	202	54	202	0								
8-10-31-18W4	m	361	337	24	293	44														
8-12-31-17W4	m	355	305	50	289	16	242	47	195	47										
7-10-31-16W4	m	289	230	59	222	8	155	67	127	28										
6-4-31-15W4	m	276	216	60	211	5														
7-32-32-28W4	m	912	912	0	815	97	815	0	722	93	722	0	590	132	590	0	512	78	449	63
6-28-32-27W4	m	829	829	0	748	81	748	0	652	96	652	0	550	102	550	0	459	91	398	61
13-25-32-26W4	ft.	2190	2180	10	1920	260	1920	0	1655	265	1655	0	1270	385	1270	0	970	300	800	170
14-15-32-25W4	m	625	616	9	552	64	552	0	459	93	459	0	331	128	331	0	245	86	193	52
10-23-32-24W4	ft.	1830	1815	15	1590	225	1575	15	1275	300	1275	0	893	382	893	0	610	283		
14-16-32-23W4	m	535	526	9	460	66	455	5	380	75	380	0	253	127	253	0				
6-27-32-22W4	m	475	464	11	404	60	393	11	312	81	312	0	187	125						
6-35-32-21W4	m	431	415	16	360	55	351	9	247	104										
11-19-32-20W4	ft.	1290	1210	80	1070	140	1020	50	725	295										
6-5-32-19W4	m	343	324	19	286	38	265	21												
11-29-32-18W4	m	350	326	24	295	31	227	68	187	40										
10-16-32-17W4	m	290	265	25	230	35	152	78	126	26										
14-31-32-16W4	m	289	242	47	225	17														
2-18-32-15W4	m	260	210	50	198	12														
11-18-33-28W4	m	897	897	0	815	82	815	0	701	114	701	0	590	111	590	0	492	98	427	65
6-28-33-27W4	m	851	851	0	740	111	740	0	625	115	625	0	515	110	515	0	420	95	364	56
11-18-33-26W4	ft.	2398	2392	6	2135	257	2120	15	1765	355	1765	0	1370	395	1370	0	1065	305	865	210
6-32-33-25W4	m	670	667	3	590	77	582	8	490	92	490	0	360	130	360	0	280	80	208	75
8-12-33-24W4	m	570	563	7	498	65	482	16	395	87	395	0	276	119	276	0	195	81		
14-2-33-23W4	m	485	477	8	420	57	405	15	307	98	307	0								
6-4-33-22W4	ft.	1670	1610	60	1495	115	1430	65	1115	315	1115	0	735	380						
13-29-33-21W4	m	486	465	21	433	32	415	18	324	91	321	3								
6-1-33-20W4	m	390	360	30	336	24	295	41	234	61	229	5								
11-5-33-19W4	m	380	345	35	308	37	286	22	216	70	212	4								

Appendix B
Horseshoe Canyon Formation subsurface tops

Well location	ft. or m	Top BLRV	Top low BRPW	Isop low BRPW	Top STHM	Isop STHM	Top mid BRPW	Isop mid BRPW	Top HDOO	Isop HDOO	Top upp BRPW	Isop upp BRPW	Top MDLD	Isop MDLD	Top DMT	Isop DMT	Top TLMN	Isop TLMN	Top CRBN	Isop CRBN
14-13-33-18W4	m	311	287	24	247	40	226	21												
13-3-33-17W4	m	315	270	45	254	16	179	75												
11-32-33-16W4	m	250	203	47	190	13														
11-10-33-15W4	ft.	740	605	135	565	40														
3-13-34-29W4	m	910	910	0	840	70	840	0	740	100	740	0	627	113	627	0	537	90	476	64
5-10-34-28W4	m	873	873	0	805	68	805	0	693	112	693	0	588	105	588	0	503	85	448	59
10-22-34-27W4	ft.	2470	2458	12	2255	203	2255	0	1870	385	1870	0	1570	300	1570	0	1310	260	1082	235
13-28-34-26W4	m	725	720	5	663	57	663	0	548	115	548	0	446	102	446	0	364	82		
6-3-34-25W4	ft.	1965	1950	15	1760	190	1745	15	1370	375	1370	0	1070	300	1070	0	780	290		
11-8-34-24W4	m	608	605	3	554	51	540	14	425	115	425	0	326	99	326	0	248	78		
14-16-34-23W4	m	553	549	4	507	42	492	15	372	120	372	0	280	92	280	0	203	77		
7-17-34-22W4	m	501	491	10	460	31	440	20	324	116	320	4	225	95	225	0				
8-19-34-21W4	m	455	442	13	414	28	402	12	275	127	268	7								
14-6-34-20W4	m	405	383	22	355	28	338	17	226	112	223	3								
13-34-34-19W4	m	373	338	35	315	23	280	35	195	85										
16-32-34-18W4	m	302	266	36	246	20	195	51												
13-27-34-17W4	m	292	246	46	237	9	160	77												
6-12-34-16W4	ft.	950	770	180	740	30	470	270												
14-10-35-28W4	m	877	877	0	791	86	791	0	688	103	688	0	558	130	558	0	476	82	415	61
14-5-35-27W4	m	830	830	0	755	75	755	0	647	108	647	0	545	102	545	0	455	90	403	52
9-32-35-26W4	m	745	745	0	679	66	675	4	567	108	567	0	470	97	470	0	392	78	340	52
6-19-35-25W4	m	643	640	3	578	62	575	3	464	111	464	0	375	89	375	0	290	85	238	52
8-8-35-24W4	m	613	606	7	553	53	540	13	425	115	425	0	342	83	342	0	261	81	215	49
7-2-35-23W4	ft	1840	1825	15	1660	165	1620	40	1250	370	1250	0	950	300	950	0	705	245	560	145
15-28-35-22W4	m	515	505	10	461	44	455	6	335	120	335	0	245	90	245	0				
7-30-35-21W4	m	449	430	19	397	33	373	24	257	116	257	0	175	82						
10-11-35-20W4	m	382	357	25	335	22	295	40	198	97	193	5								
6-5-35-19W4	m	392	353	39	338	15	280	58	208	72	201	7								
8-20-35-18W4	m	322	277	45	267	10	195	72												
11-16-35-17W4	ft.	960	800	160	775	25	525	250												
11-21-35-16W4	m	289	235	54	229	6														
6-7-35-15W4	m	270	214	56	210	4														
3-13-36-28W4	m	798	798	0	715	83	715	0	615	100	615	0	500	115	500	0	415	65	368	47
14-35-36-27W4	m	789	789	0	706	83	706	0	618	88	618	0	485	133	485	0	410	75	360	50
16-9-36-26W4	m	734	734	0	667	67	667	0	563	104	563	0	461	102	461	0	365	96	323	44
14-30-36-25W4	m	745	743	2	685	58	681	4	576	105	576	0	465	111	465	0	370	95	317	53
12-11-36-24W4	m	642	639	3	595	44	590	5	463	127	463	0	358	105	358	0	273	85	208	72
7-29-36-23W4	ft	2010	1970	40	1840	130	1825	15	1440	385	1440	0	1085	355	1085	0	800	285		
14-18-36-22W4	m	592	578	14	540	38	537	3	420	117	417	3	312	105	312	0	235	77		
9-28-36-21W4	m	517	506	11	460	46	452	8	350	102	348	2	240	108	240	0				
4-36-36-20W4	ft.	1270	1190	80	1075	115	1040	35	727	313	715	12	350	365	350	0				
13-22-36-19W4	m	395	365	30	335	30	310	25	235	75	232	3								
16-3-36-18W4	m	310	283	27	255	28	217	38	150	67										
5-13-36-17W4	m	270	226	44	213	13	160	53	120	40										
10-25-36-16W4	m	253	198	55	198	0	130	68												
16-28-36-15W4	m	207	155	52	155	0														

Appendix B
Horseshoe Canyon Formation subsurface tops

Well location	ft. or m	Top BLRV	Top low BRPW	Isop low BRPW	Top STHM	Isop STHM	Top mid BRPW	Isop mid BRPW	Top HDOO	Isop HDOO	Top upp BRPW	Isop upp BRPW	Top MDLD	Isop MDLD	Top DMT	Isop DMT	Top TLMN	Isop TLMN	Top CRBN	Isop CRBN
10-21-37-28W4	ft.	2585	2585	0	2360	225	2360	0	2000	360	2000	0	1625	375	1625	0	1310	315	1200	110
14-17-37-27W4	m	750	750	0	658	92	658	0	540	118	540	0	435	105	435	0	345	90	298	50
6-29-37-26W4	m	727	727	0	665	62	665	0	545	120	545	0	450	95	450	0	353	97		
11-17-37-25W4	m	715	715	0	655	60	655	0	540	115	540	0	430	110	430	0	343	87	295	48
4-4-37-24W4	m	616	616	0	557	59	555	2	435	120	435	0	354	81	354	0	255	99		
6-25-37-23W4	m	525	521	4	470	51	465	5	343	122	343	0	264	79	264	0	177	87		
13-20-37-22W4	m	535	525	10	480	45	476	4	360	116	360	0	277	83	277	0	194	83		
12-26-37-21W4	ft	1210	1175	35	1010	165	975	35	640	335	635	5	365	270	365	0	100	265		
1-27-37-20W4	ft	1170	1120	50	990	130	940	50	625	315	620	5	370	250	370	0	90	280		
6-28-38-28W4	ft	2725	2725	0	2468	257	2468	0	2085	383	2085	0	1750	335	1750	0	1490	260	1300	190
2-11-38-27W4	ft.	2270	2260	10	2050	210	2050	0	1670	380	1670	0	1320	350	1320	0	1075	245	900	175
16-9-38-26W4	m	755	753	2	690	63	690	0	568	122	568	0	472	96	472	0	400	72	335	65
6-20-38-25W4	m	505	498	7	445	53	442	3	328	114	328	0	231	97	231	0	148	83		
13-34-38-24W4	m	487	480	7	427	53	424	3	302	122	302	0	210	92	210	0				
8-21-38-23W4	m	468	462	6	411	51	408	3	292	116	291	1	180	111	180	0				
3-36-38-22W4	ft	1240	1210	30	1060	150	1040	20	670	370	650	20								
10-2-38-21W4	m	360	350	10	310	40	300	10												
14-3-38-20W4	ft	1120	1070	50	950	120	920	30	545	375	520	25	210	310						
11-3-39-28W4	m	760	760	0	694	66	694	0	557	137	557	0	476	81	476	0	390	86	328	62
11-1-39-27W4	m	662	662	0	596	66	596	0	460	136	460	0	385	75	385	0	307	78	245	65
1-9-39-26W4	ft	2175	2175	0	1960	215	1960	0	1540	420	1540	0	1260	280	1260	0	940	320	795	145
6-16-39-25W4	m	614	610	4	551	59	548	3	428	120	428	0	340	88	340	0				
12-26-39-24W4	ft.	1900	1885	15	1690	195	1680	10	1085	595	1085	0	760	325	760	0	450	310		
9-6-39-23W4	ft.	1460	1445	15	1260	185	1250	10	840	410	840	0								
14-25-39-22W4	m	395	380	15	343	37	336	7												
5-29-39-21W4	m	438	425	13	381	44	374	7	244	130	244	0								
12-6-39-20W4	m	379	366	13	321	45	312	9	184	128	181	3								
6-14-40-28W4	m	744	744	0	676	68	676	0	551	125	551	0	465	86	465	0	379	86	330	49
8-7-40-27W4	m	730	730	0	670	60	670	0	545	125	545	0	445	100	445	0	370	75	309	67
7-24-40 26W4	ft	2330	2320	10	2145	175	2145	0	1695	450	1695	0	1395	300	1395	0	1150	245	930	220
10-5-40-25W4	ft	2130	2105	25	1940	165	1940	0	1465	475	1465	0	1160	305	1160	0	937	223	720	217
16-17-40-24W4	m	605	595	10	550	45	546	4	402	144	402	0	317	85	317	0	242	75	192	62
14-33-40-23W4	m	515	491	24	460	31	453	7	307	146	307	0	225	82	225	0	149	76	98	57
6-4-40-22W4	m	400	373	27	340	33	322	18	187	135	187	0								
13-29-40-21W4	m	364	322	42	295	27	282	13	160	122	154	6	75	79						
6-6-40-20W4	m	381	334	47	323	11	292	31	189	103	174	15								

Appendix C
Horseshoe Canyon Formation Gas Pools, Alberta

(pools located primarily to north and west but * = those within the present study area, from Hamblin and Lee, 1997)

Strathmore tongue: av. GIP 8.2 $\times10^6$ m^3; av. net pay 3.5 m, av. porosity 27%

Field	Pool	Discovery well	Interval (m)
*Cessford	Edm A	7-4-28-16W4	202–208
*Farrell	Edm und	16-32-34-16W4	223–227
*Leo	Edm und	8-9-36-17W4	205–209
*Leo	BR und	13-17-36-17W4	208
Leo	BR und	10-19-36-17W4	207
McLeod	BR und	7-15-56-14W5	691–693
*Rowley	Brpw und	11-12-33-20W4	297–307

Hoodoo tongue: av. GIP 45.0 $\times10^6$ m^3; av. net pay 5.3 m; av. porosity 25%

Field	Pool	Discovery well	Interval (m)
Bigoray	Edm und	14-23-53-8W5	481–497
*Bashaw-Nevis	Edm und	13-32-40-21W4	291–299
*Bashaw-Nevis	Edm D	8-4-41-22W4	289–290
*Bashaw-Nevis	Edm und	13-1-41-22W4	286–293
Chickadee	Edm und	9-15-61-16W5	561–568
*Entice	Edm und	11-16-27-24W4	128–133
*Farrow	Edm und	10-29-19-24W4	550–552
Ferrybank	Edm und	7-15-43-28W4	583–589
Leaman	BR und	6-16-56-9W5	400
*Leo	BR und	6-11-35-17W4	220
*Michichi	BR und	11-1-30-18W4	277–280
Pembina	BR und	10-35-46-2W5	560–578
Pembina	BR und	6-34-47-3W5	612–614
Pembina	BR und	11-7-47-5W5	725–728
Pembina	BR und	10-13-47-5W5	666–670
Pembina	BR und	12-32-47-5W5	512–517
Sylvan Lake	Edm und	6-23-37-3W5	887–896

Midland tongue: av. GIP 12.8 $\times10^6$ m^3; av. net pay 3.3 m; av. porosity 24%

Field	Pool	Discovery well	Interval (m)
Chickadee	Edm A	6-5-61-16W5	461–468
Coral	Edm und	10-33-46-5W5	663–665
*Davey	Edm und	6-36-34-27W4	623–629
Ferrier	Edm und	9-29-38-7W5	1218–1220
Ferrybank	Edm und	11-33-43-27W4	368–373
Morningside	BR und	11-16-42-28W4	634–635

Tolman tongue: av. GIP 9.0 $\times10^6$ m^3, av. net pay 2.2 m; av. porosity 24%

Field	Pool	Discovery well	Interval (m)
Sylvan Lake	Edm und	7-32-36-3W5	659–669

Carbon tongue: av. GIP 16.3 $\times10^6$ m^3; av. net pay 6.3 m; av. porosity 24%

Field	Pool	Discovery well	Interval (m)
Bigoray	Pask und	10-18-51-8W5	237–252
Bigoray	Pask A	10-22-51-8W5	172–186
Lanaway	Edm und	7-32-36-3W5	610–614
Minnehik	Edm und	9-25-44-6W5	466–475
Minnehik	BR und	6-16-56-9W5	400
Sylvan Lake	Pask und	7-32-36-3W5	549–555

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The Horseshoe Canyon Formation in southern Alberta: surface and subsurface stratigraphic architecture, sedimentology, and resource potential

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